Bringing a Quantum Computer to Life with RF Pulses:

Fundamental Aspects of Pulse Level Control

Lior Ella

QUANTUM MACHINES

A bit of background about Quantum Machines

- Quantum physicists and engineers on a mission to revolutionize quantum control and unlock a new era in quantum computing and research

- Founded in 2018

- Currently about 40 employees

- Customers in almost every major research institution worldwide

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Prerequisites

- What is a qubit
- Familiarity with standard gates
- Basic understanding of quantum circuits

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Introduction

- The quantum hardware stack
- Physical implementations of quantum computers
- What is a controller and why does a quantum computer need one?

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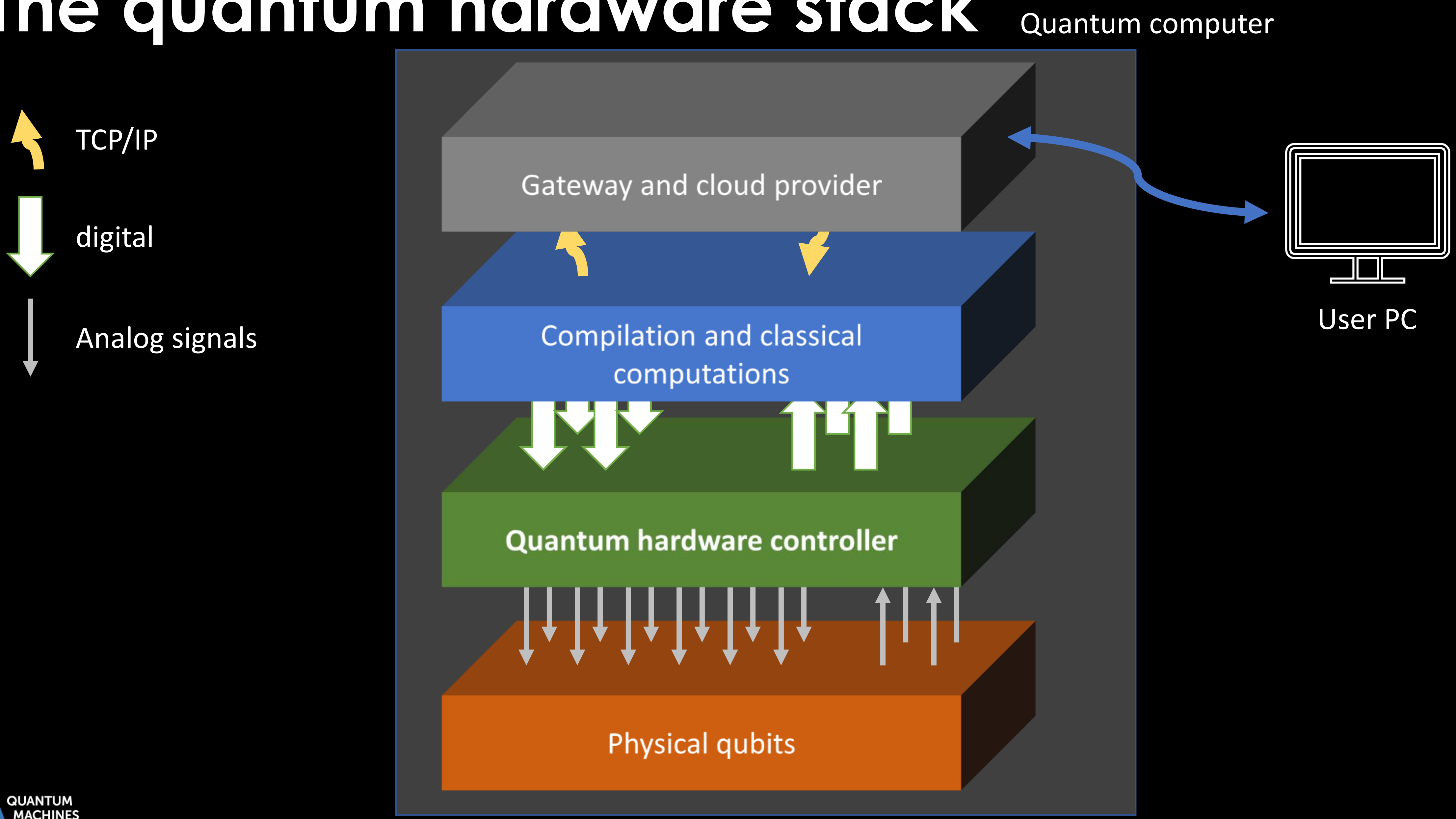
The quantum hardware stack



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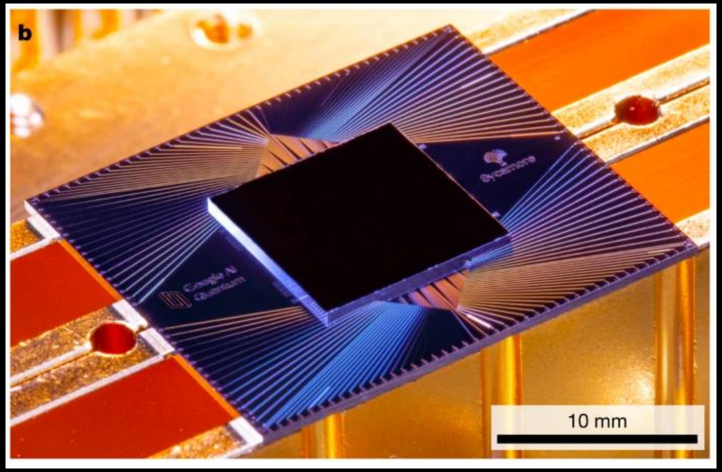
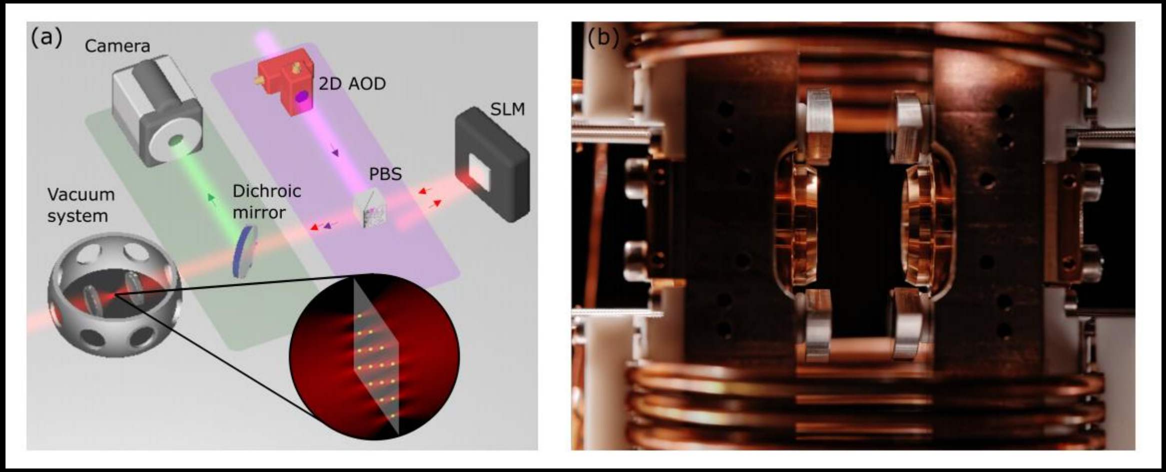
Some physical implementations of qubits

Superconducting qubits (cQED)



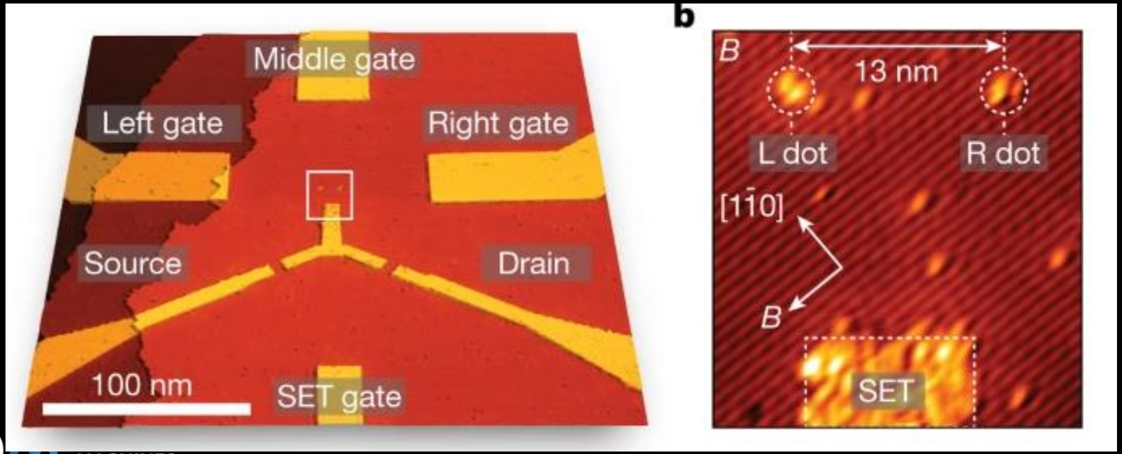
Arute et al., Nature 574, 505 (2019)

Neutral atoms



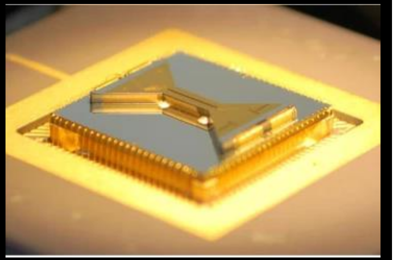
Henriet et al., Quantum 4, 327 (2020)

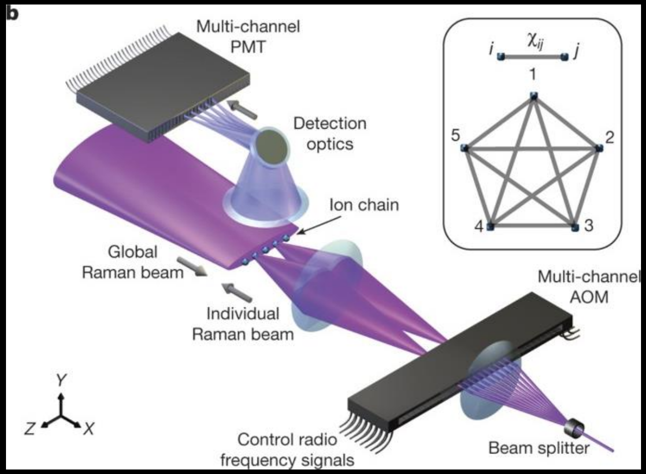
Quantum dot based Spin qubits



He et al., Nature 571, 371 (2019)

Trapped ions





Debnath et al., Nature 536, 63 (2016)

Some physical implementations of qubits

- All of these implementations have one thing in common:

- Generation of complex sequences of coherent control tones for:
  - qubit state preparation
  - Generation of quantum gates and operations
  - State readout

- These functions are all achieved using the quantum hardware controller.

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What we will discuss

- In this tutorial, we will learn about the quantum hardware controller and pulse level control.

- What does the controller do?

- What makes it unique?

- How are gates translated into actual pulses?

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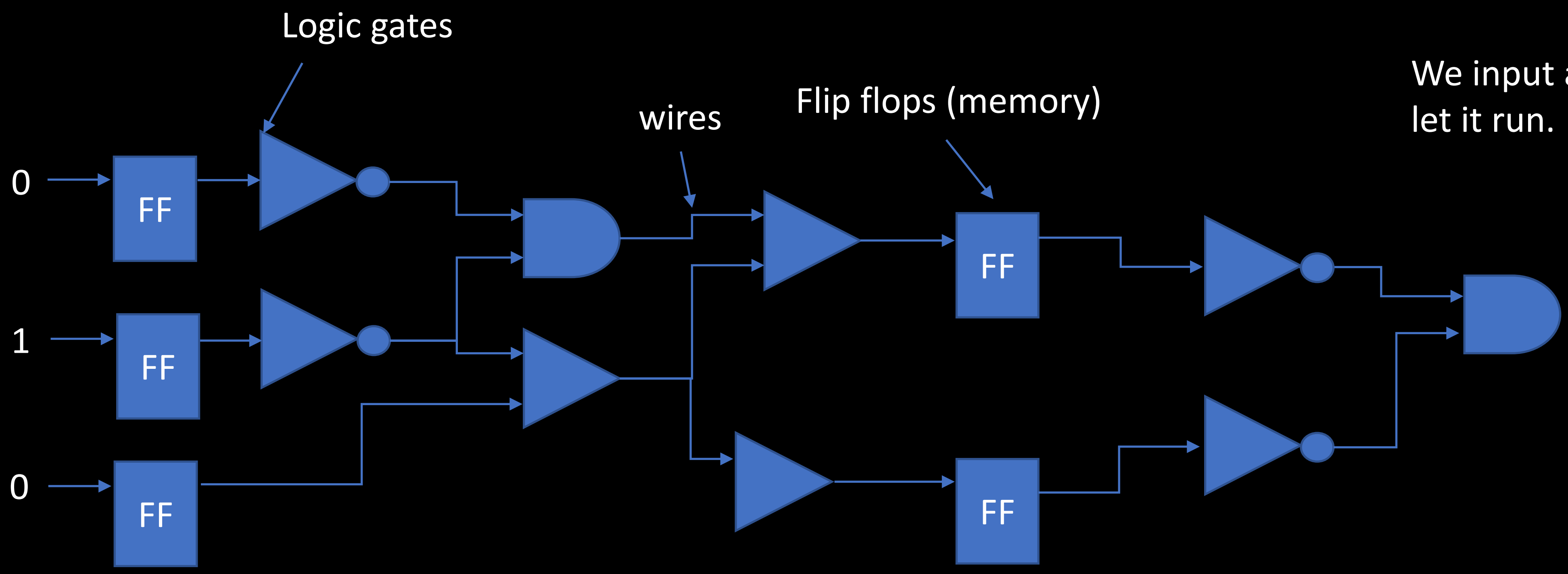
why does a quantum computer need a controller?

Computation with a classical computer

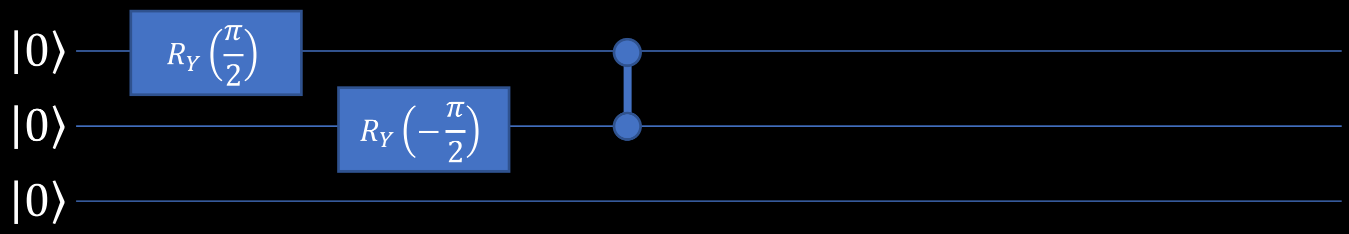


Everything is hardwired before the computation begins.

We input an initial state and let it run.

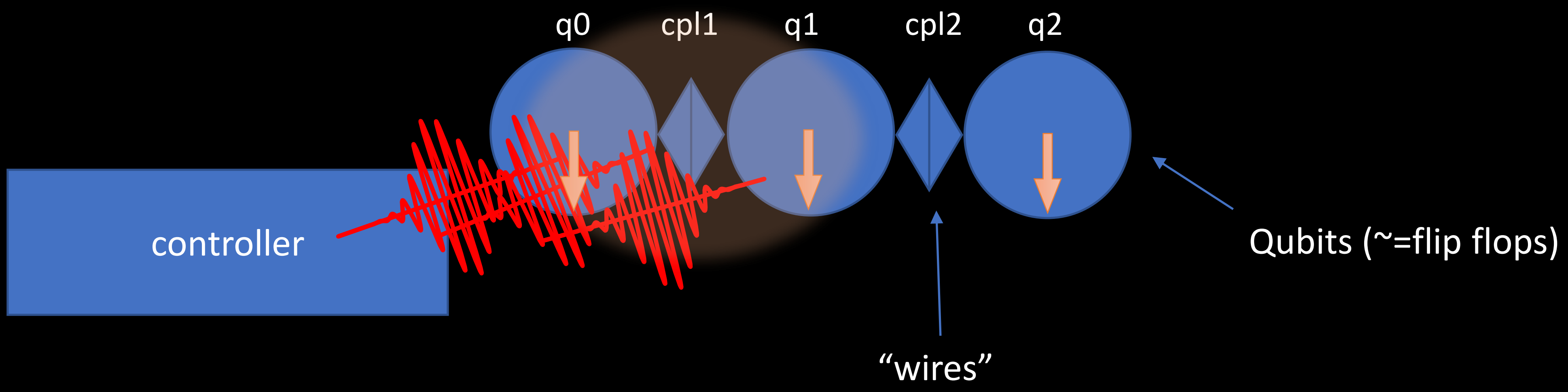
why does a quantum computer need a controller?

Computation with a quantum computer



We initialize the state

And then we need to create the gates!



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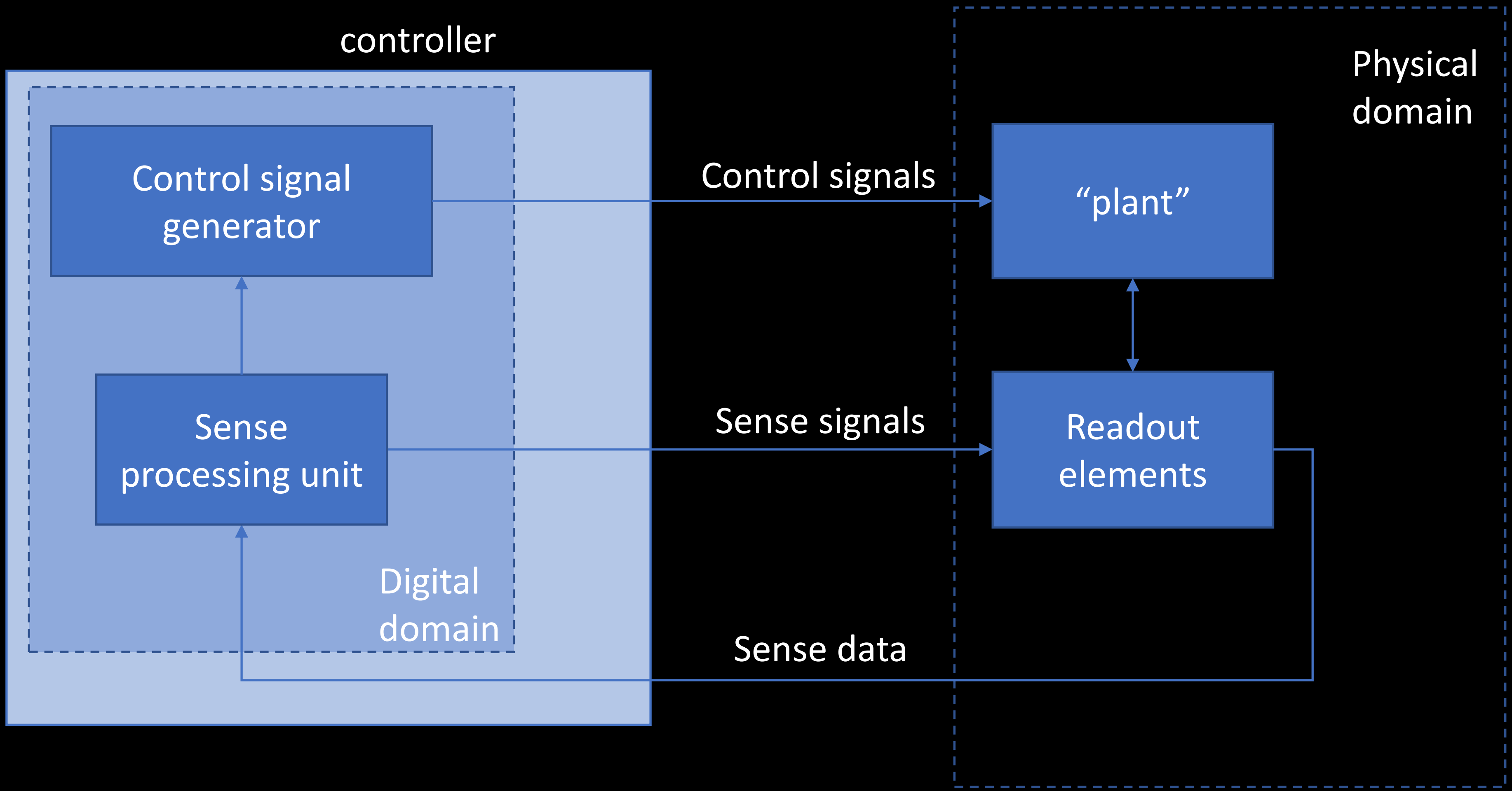
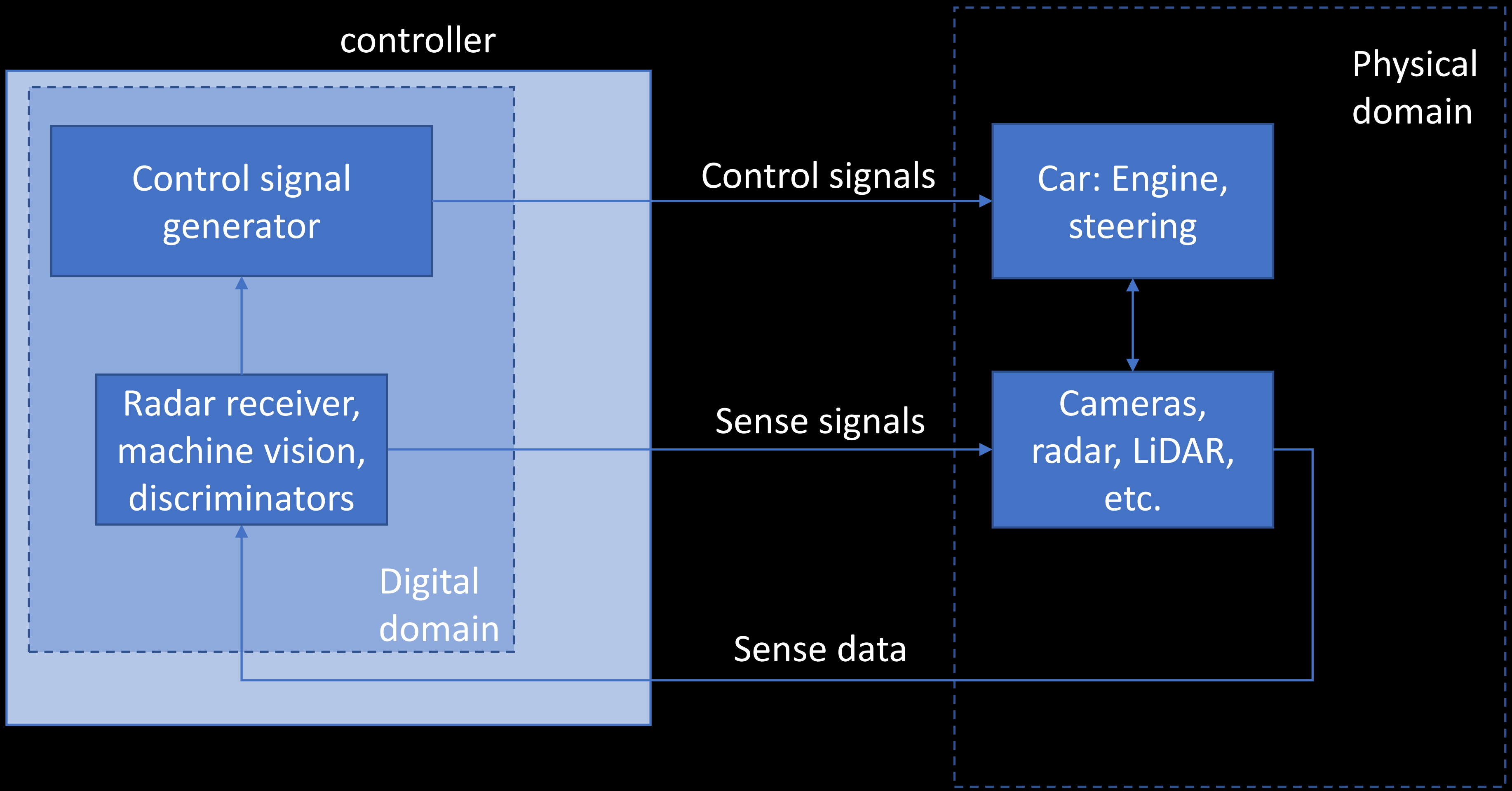
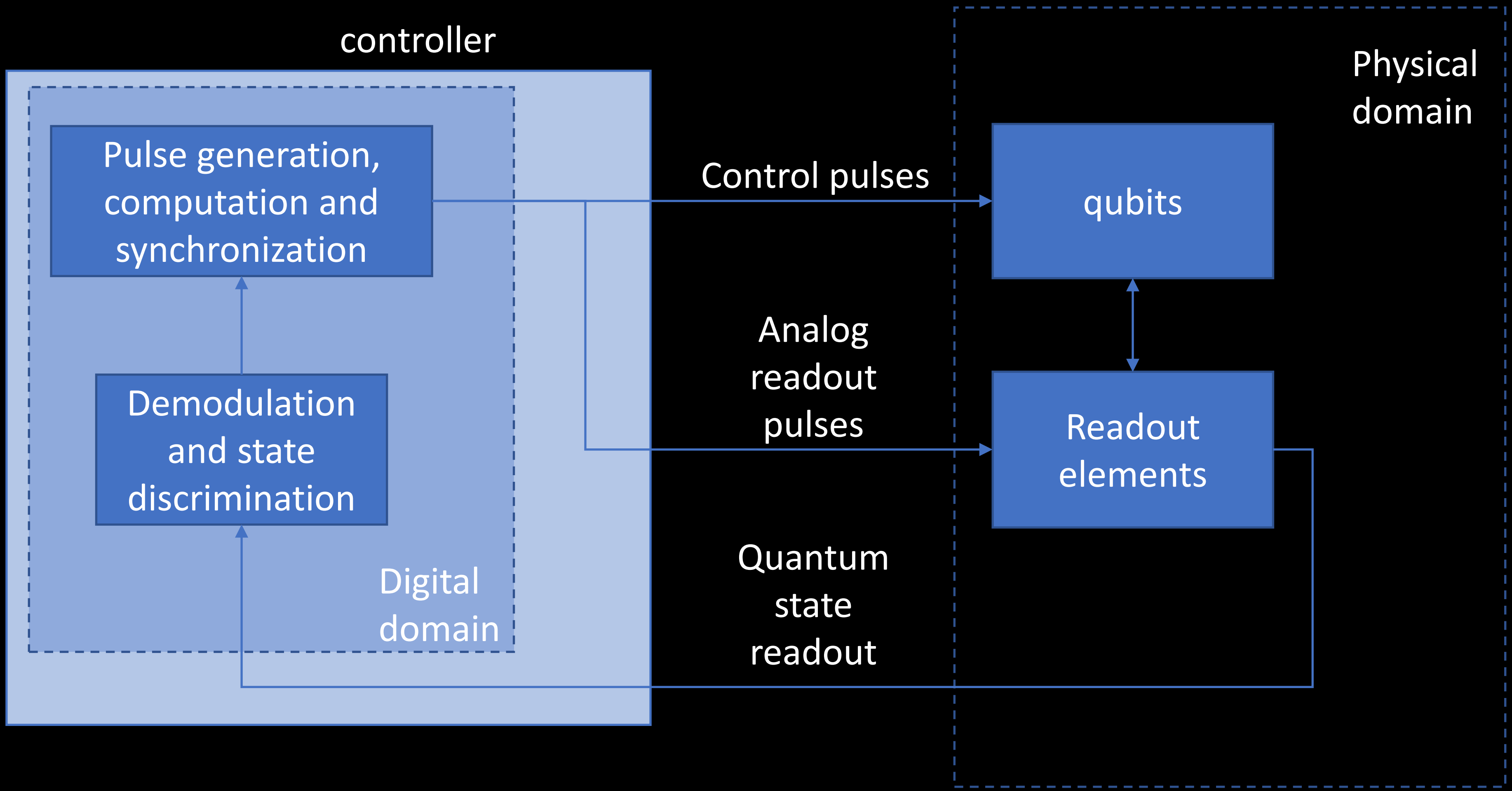
What is a controller, in general?



Examples of controllers: Autonomous vehicle



A quantum hardware controller



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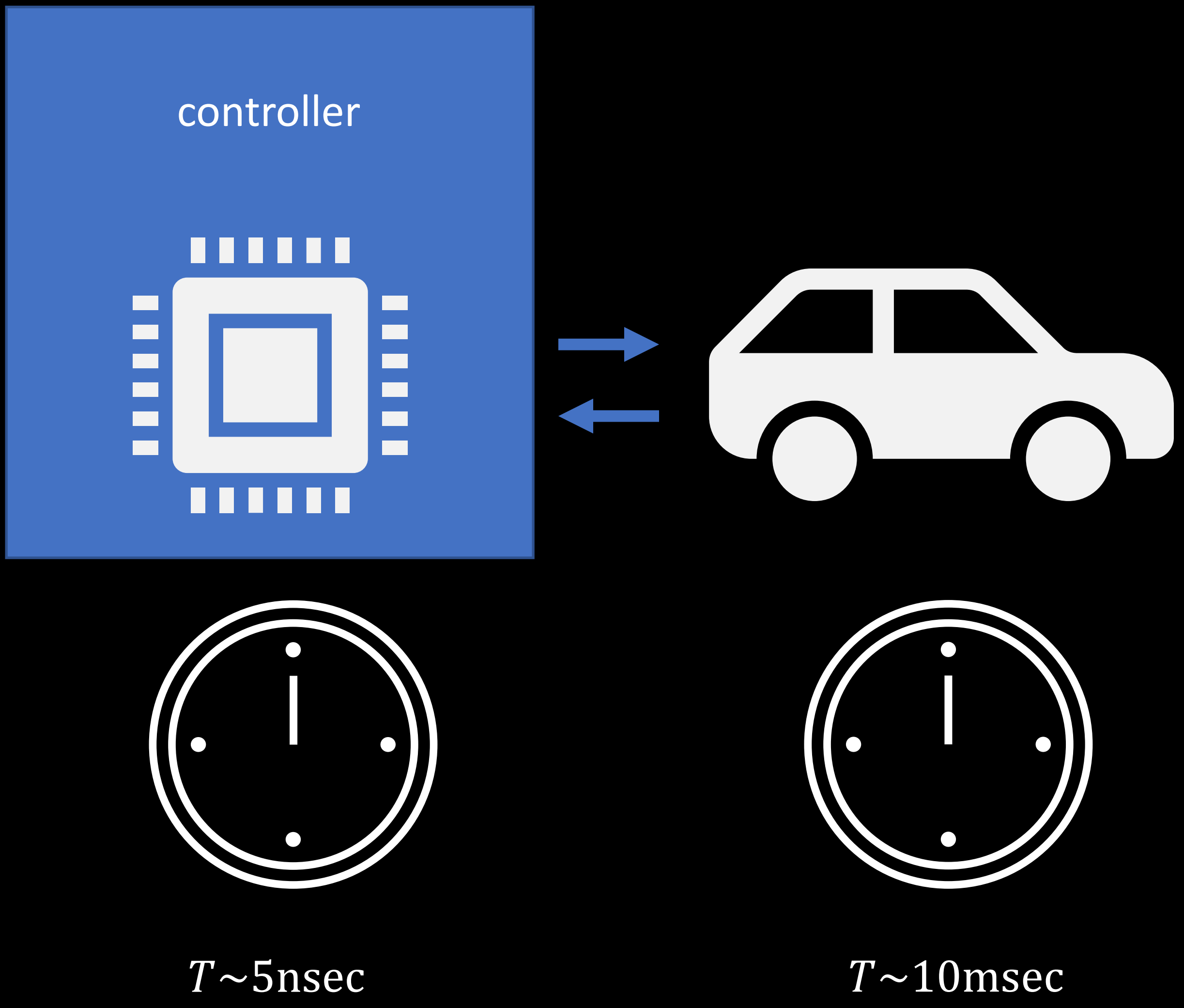
The unique requirements of a controller for a quantum computer

- In autonomous vehicles, the timescales of the controlled system are > 10's of msec.
- The clock cycle time of the controller is ~5nsec.
- => Many calculations can be performed between different events
- This is generally true for most "classical" systems



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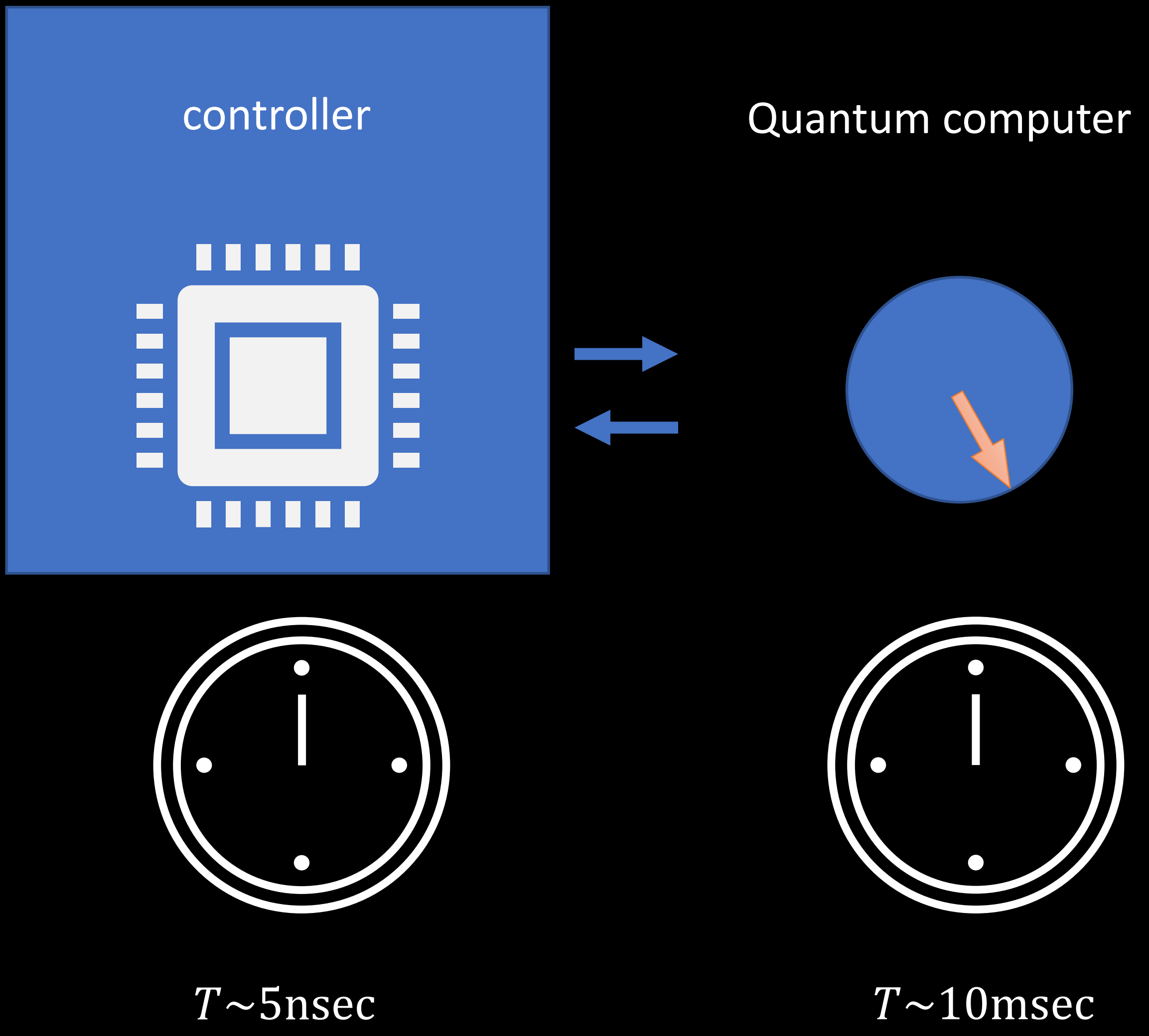
The unique requirements of a controller for a quantum computer

- In a quantum computer, the timescales of the controlled system are also ~5nsec. *
- => The calculations must happen on the timescale of the events



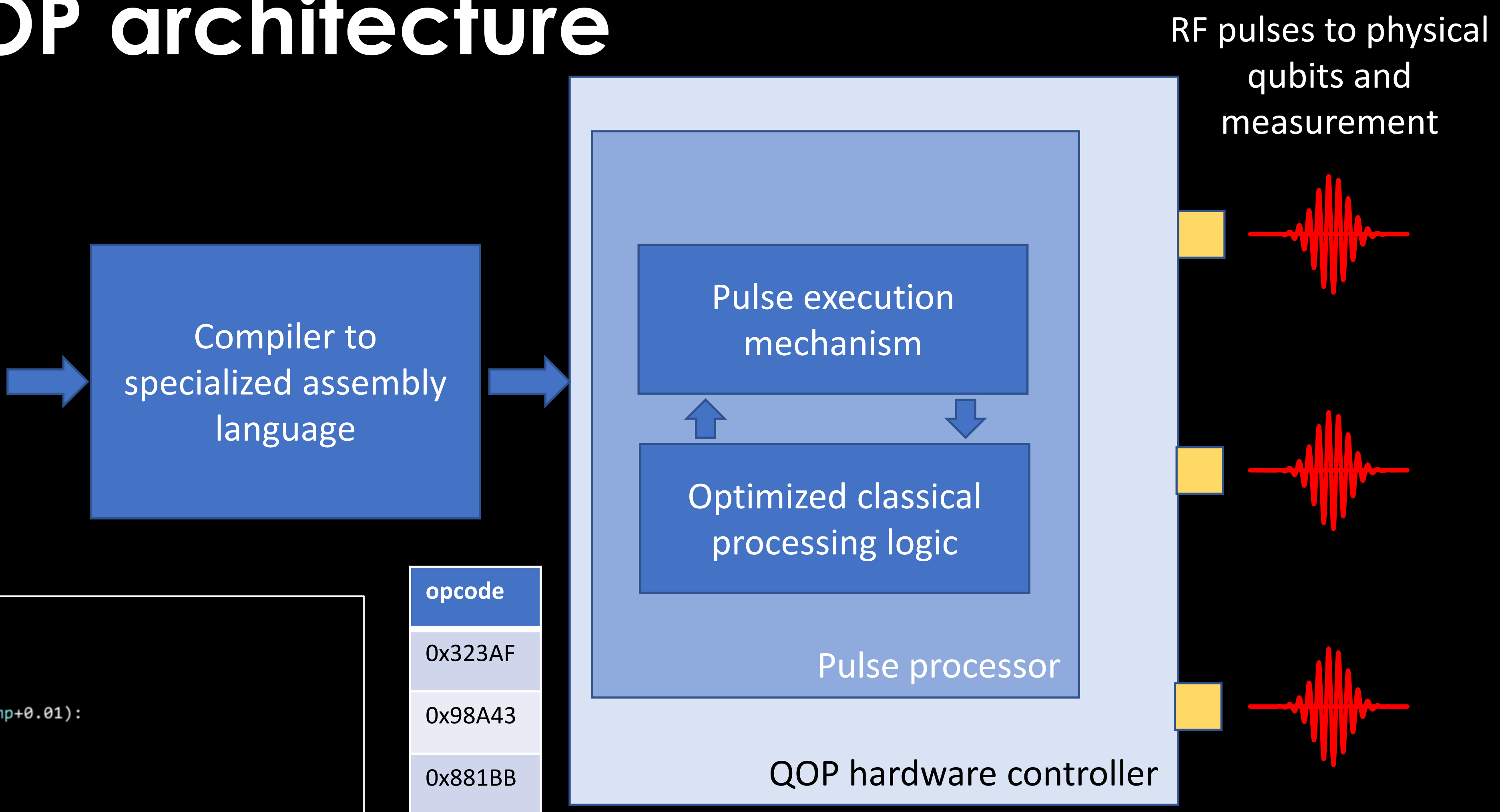
The unique requirements of a controller for a quantum computer

- Conclusion: Quantum computers require a controller that can make decisions and compute on the timescale that it controls.
- This is a very demanding requirement!
- It is achieved using the quantum orchestration platform by Quantum Machines

The QOP architecture

QUA program:
<u>Real time</u>
<u>deterministic</u>
description of:

- Pulses
- Computations
- Control flow




```
program powerRabi:
    for(n=0, n<1000, n=n+1):
        for(amp=0, amp <=1, amp=amp+0.01):
play('pi_pulse' * a, 'my_qubit')
align('my_qubit', 'my_resonator')
measure('meas_pulse', 'my_resonator', (demodulate, ‘my_weights’, I))
save(I, ‘I_result’)
save(Q, ‘Q_result’)
save(a, ‘a_result’)
```

opcode
0x323AF
0x98A43
0x881BB
…

Recap

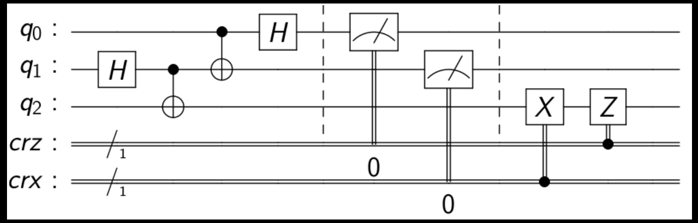
- The quantum hardware controller is at the heart of the quantum computer
- It interfaces directly with the qubits
- The performance requirements from it are unique because the timescales of the qubits are comparable to the clock cycle time

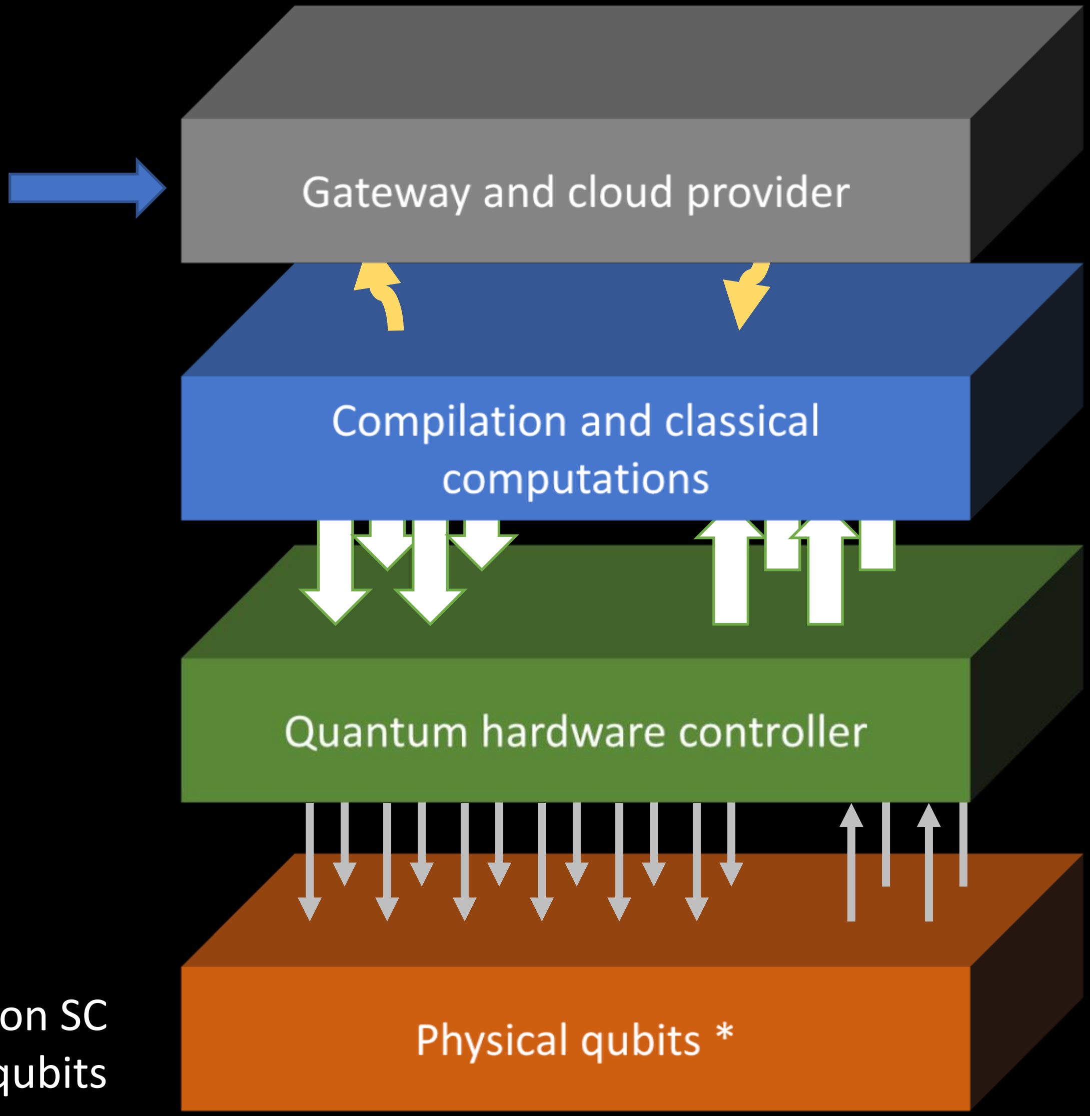
From quantum circuits to pulse sequences

- Overview of how quantum circuits are transformed into pulses
- In depth look at some of the key steps

Converting a circuit to a pulse sequence

User generated circuit





Cirq

Qiskit

QUIL

Q#

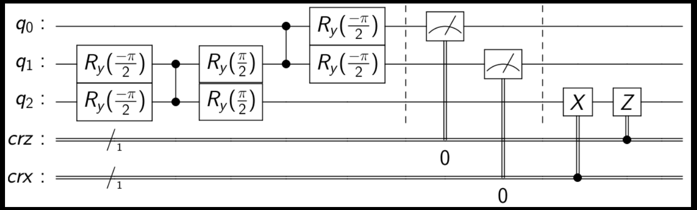
OpenQASM

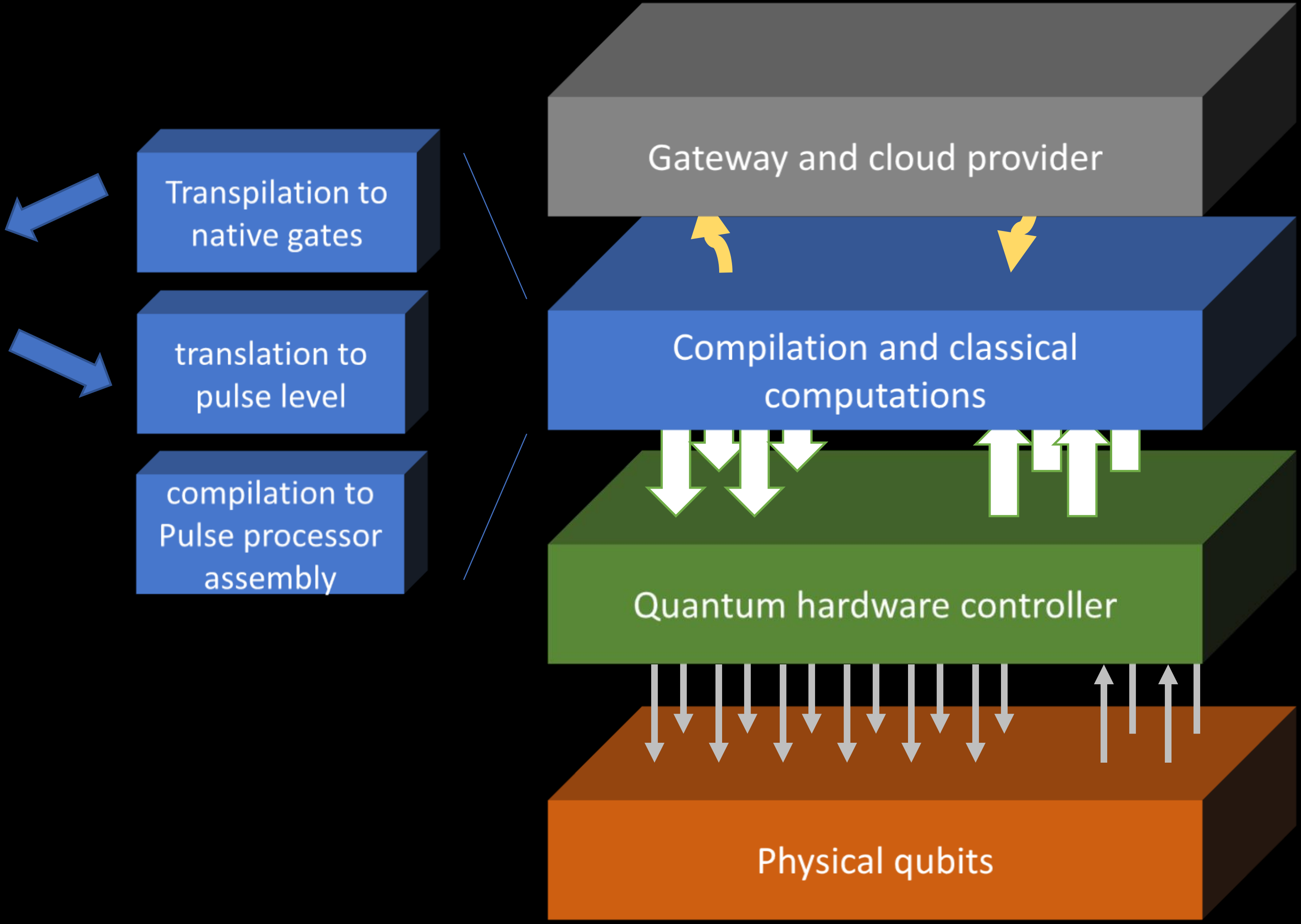
And others

* Focus on SC qubits

Converting a circuit to a pulse sequence

Circuit in
native gates





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Converting a circuit to a pulse sequence

QUA

Program in pulse level

```
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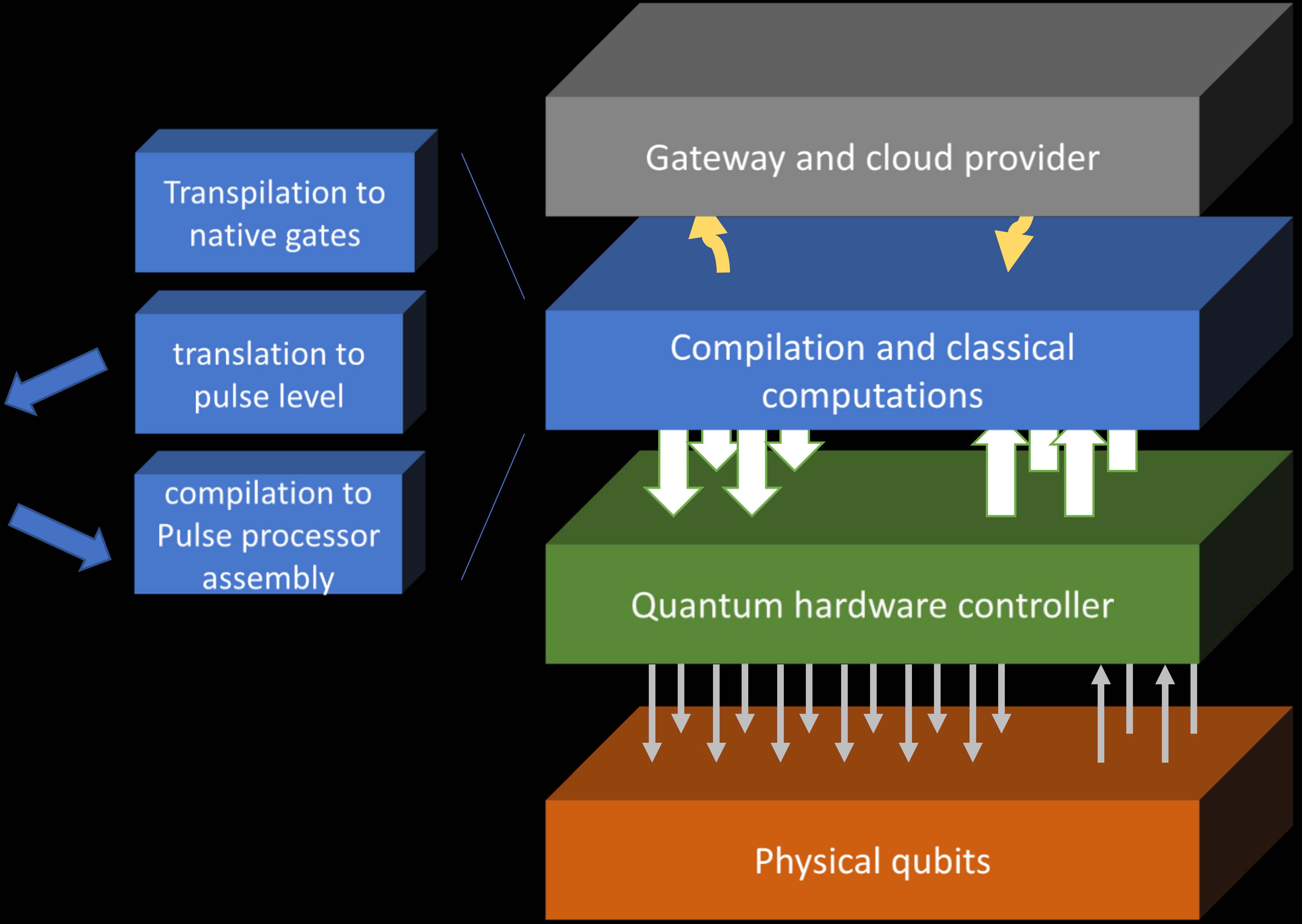

Converting a circuit to a pulse sequence

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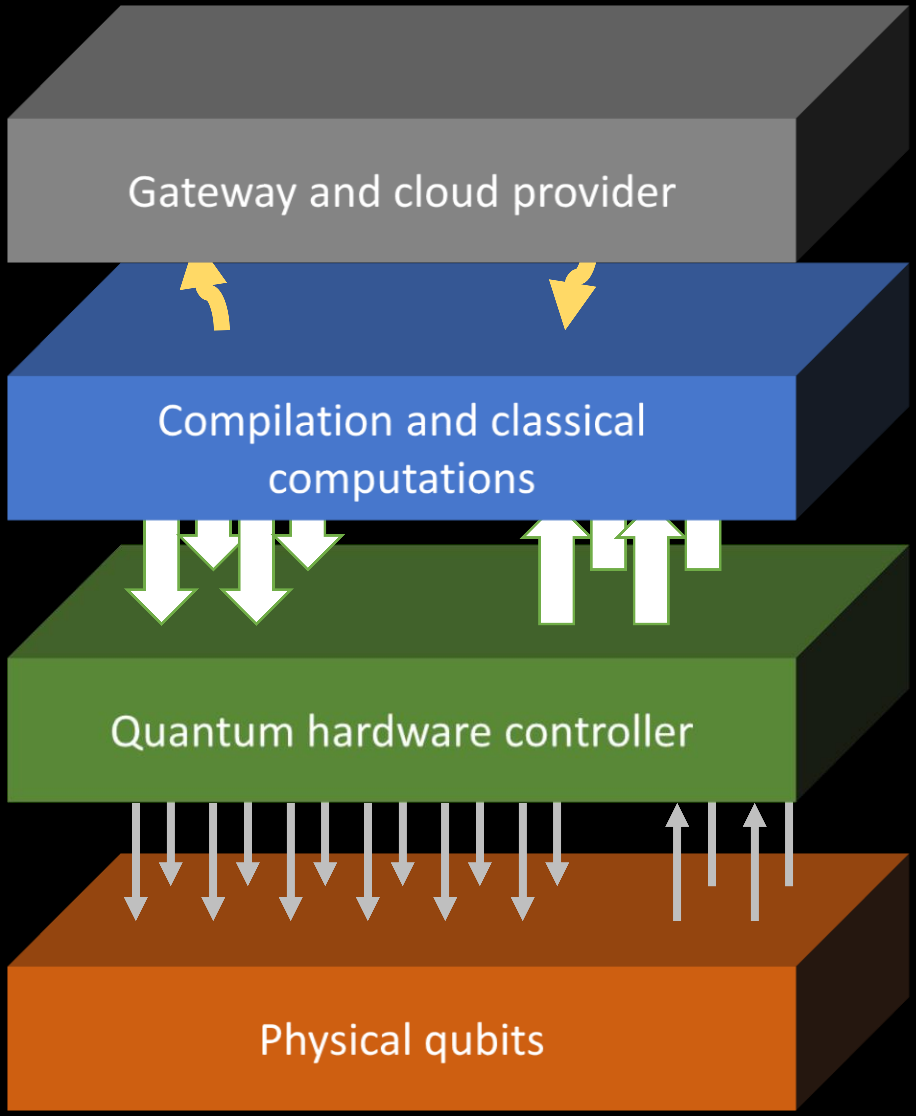
compiler

opcode
0x323AF
0x98A43
0x881BB
…



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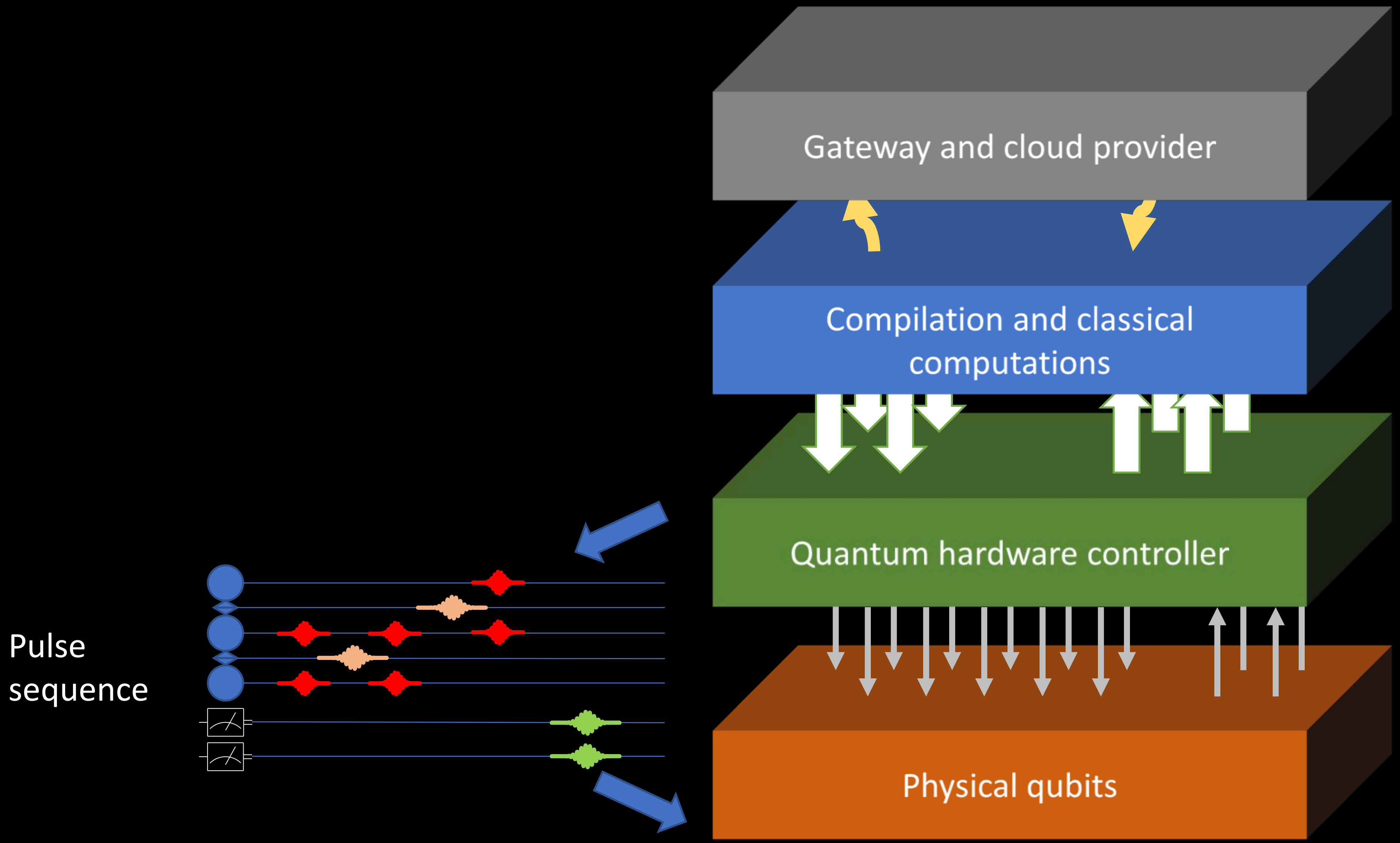
Converting a circuit to a pulse sequence



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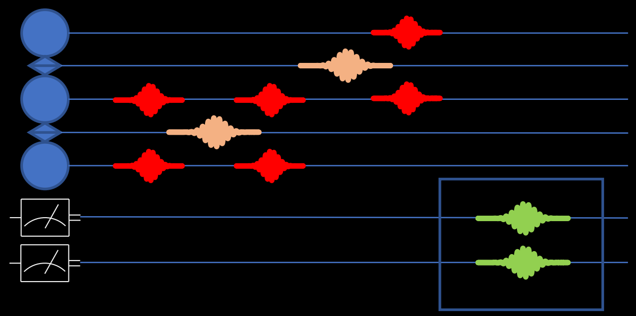
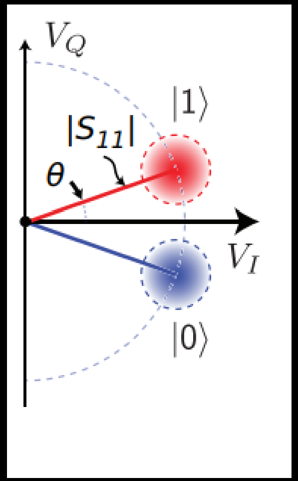
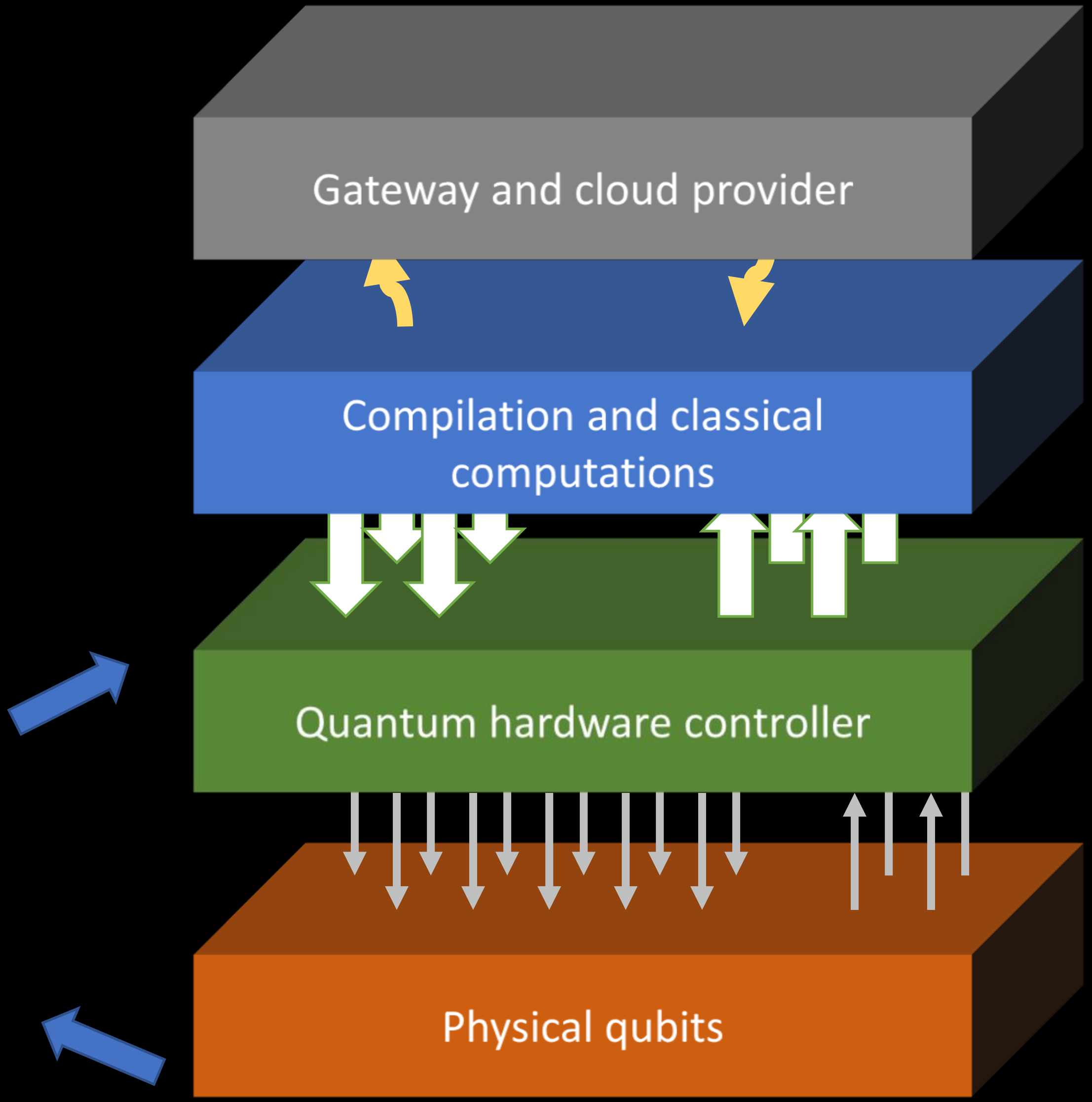
Converting a circuit to a pulse sequence

Pulse sequence



State discrimination data from qubits





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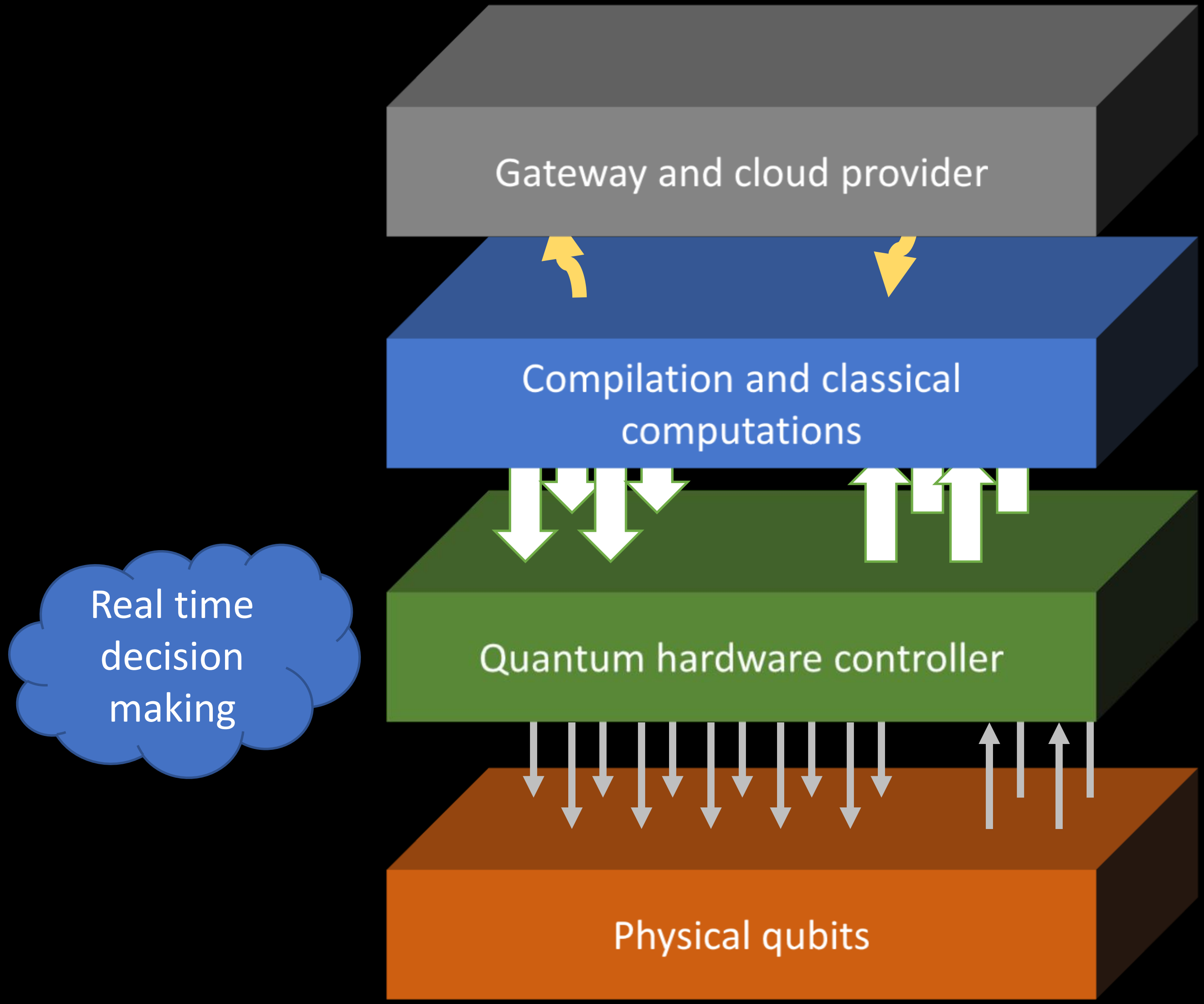
Krantz et al., Applied Physics Reviews 6, 021318 (2019)

Converting a circuit to a pulse sequence



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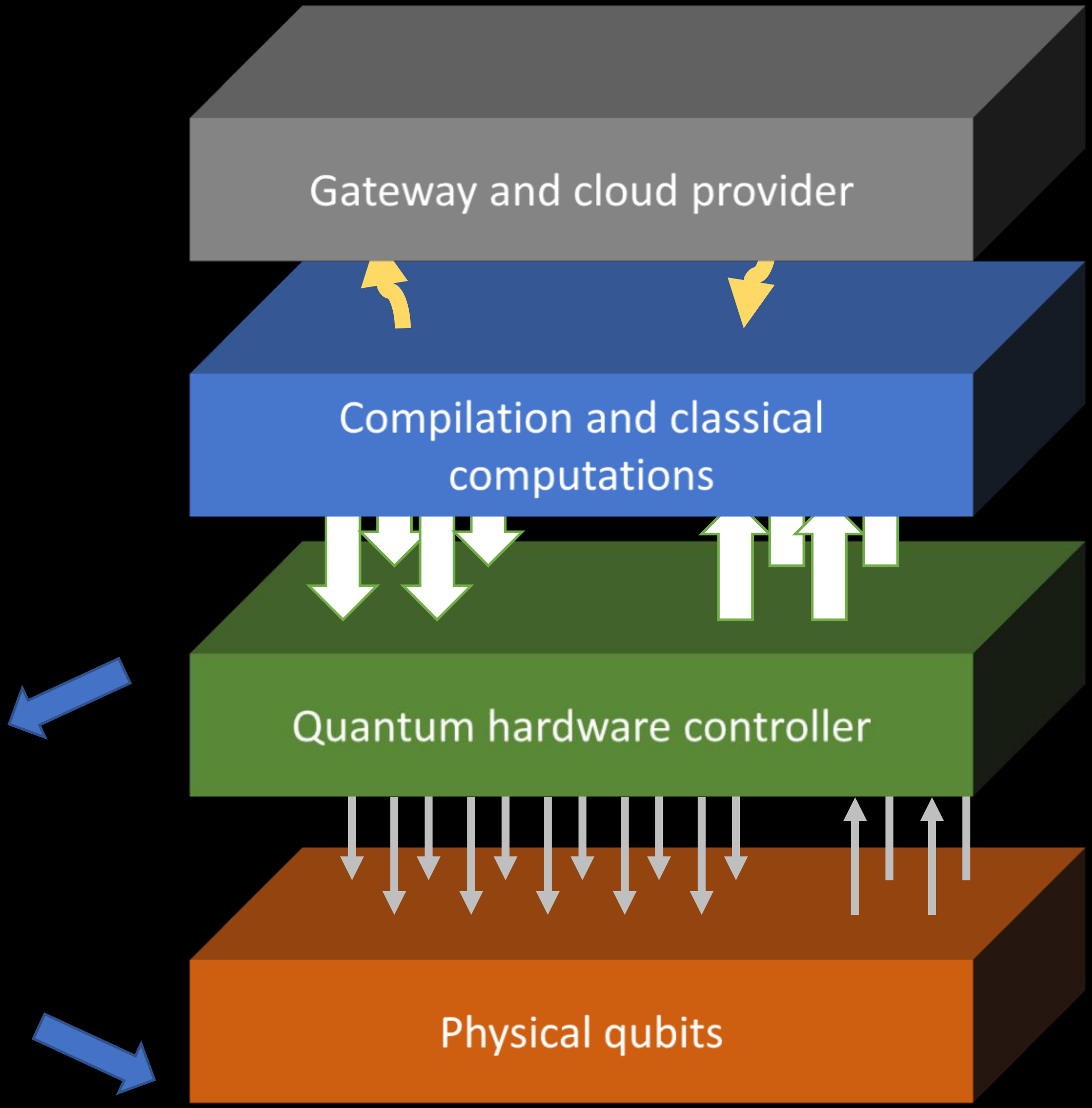
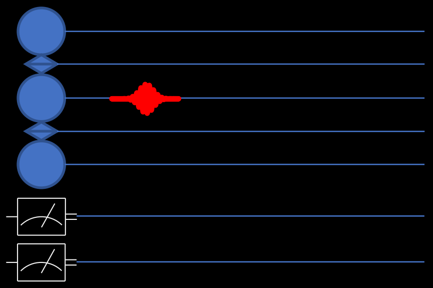
Converting a circuit to a pulse sequence



Pulse conditioned on measured result



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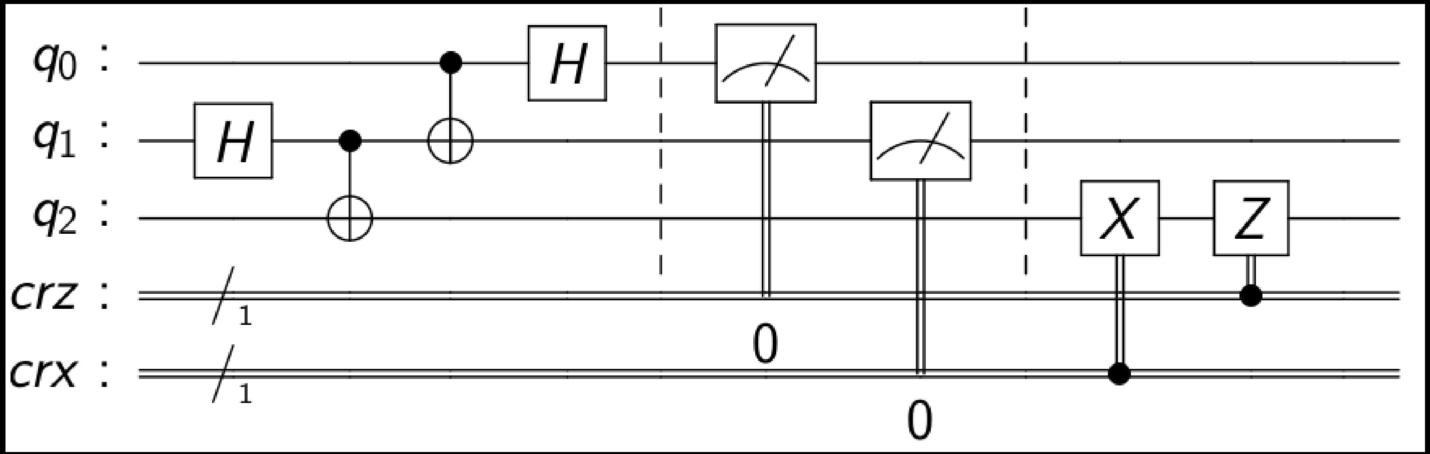
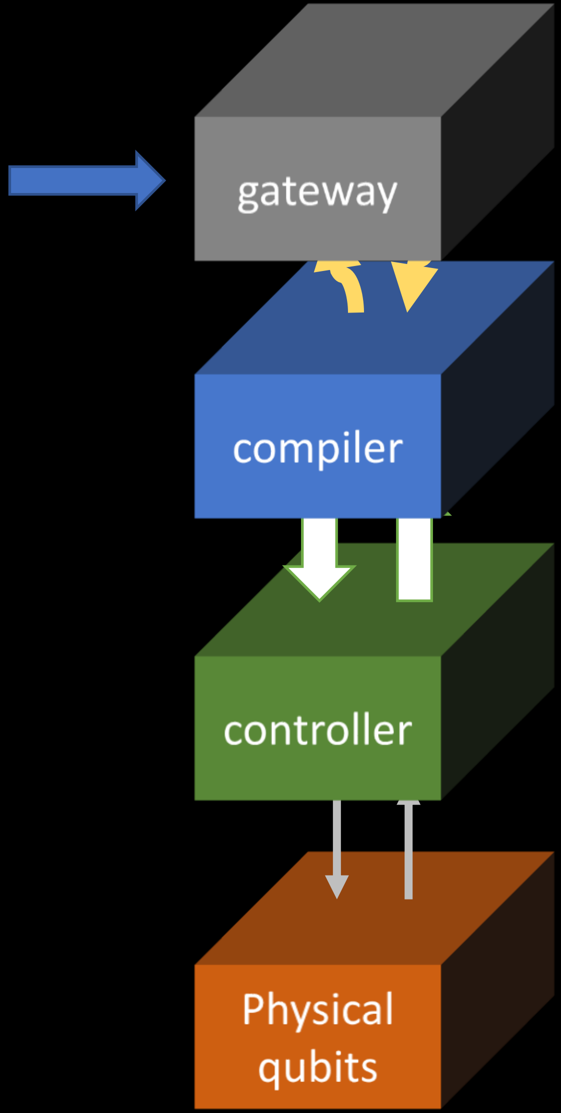
Converting a circuit to a pulse sequence

- Let's take the steps above and dive into each one.
- Example: Quantum teleportation





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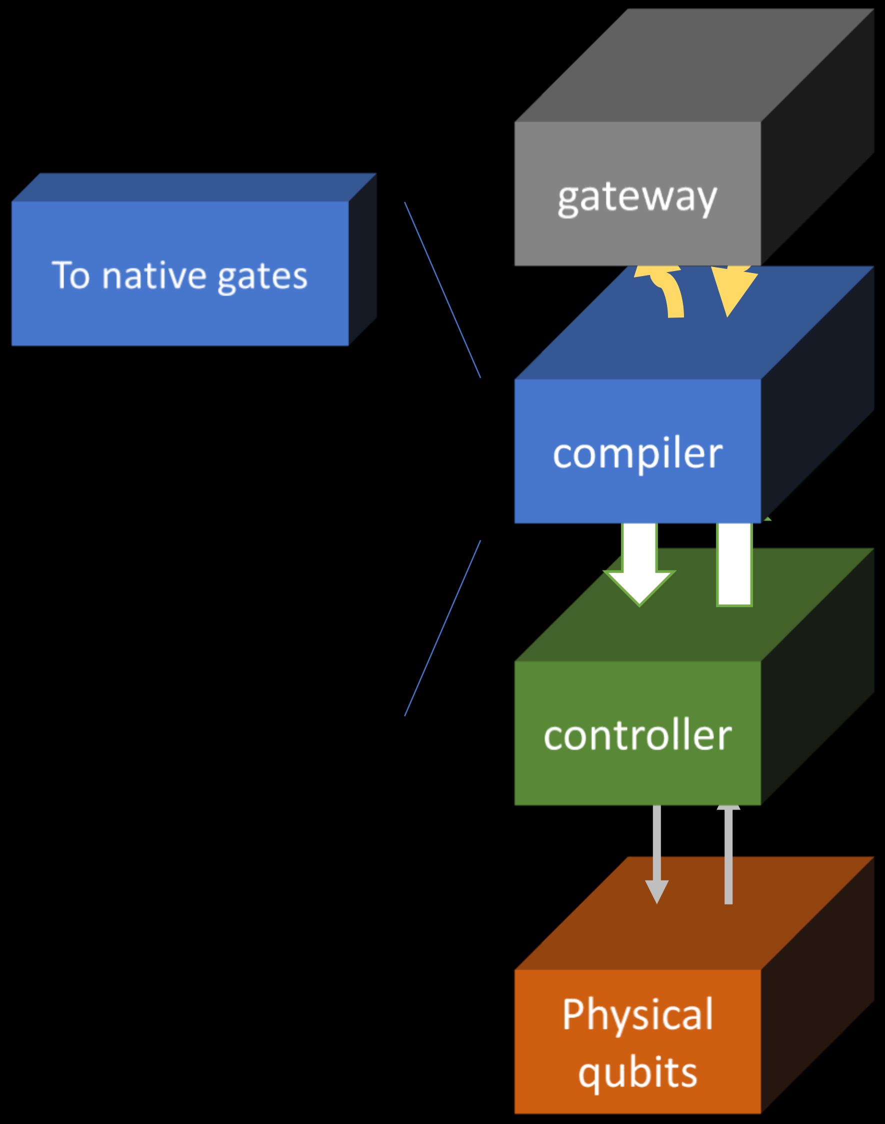
Converting a circuit to a pulse sequence

Conversion to native gates

- Transpilation: Turns the circuit into one that can be executed on a *specific* quantum computer

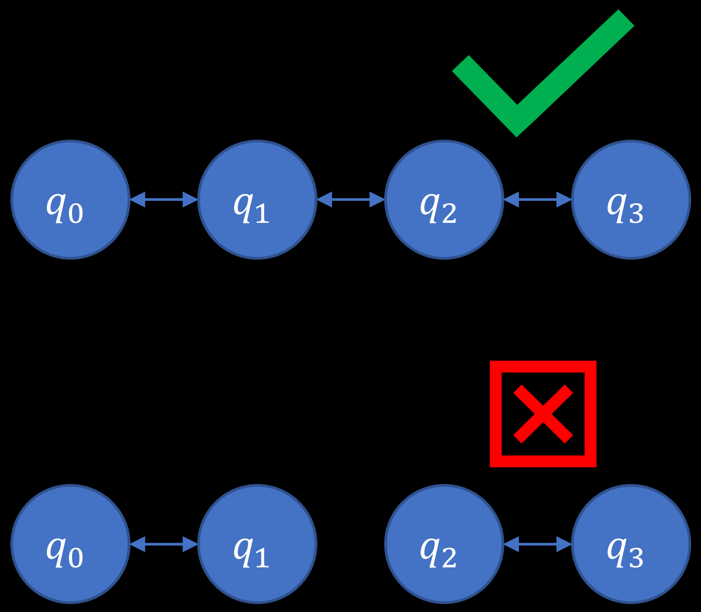
- Requirements for the transpilation to succeed:
  - Connectivity
  - Universal native gate set

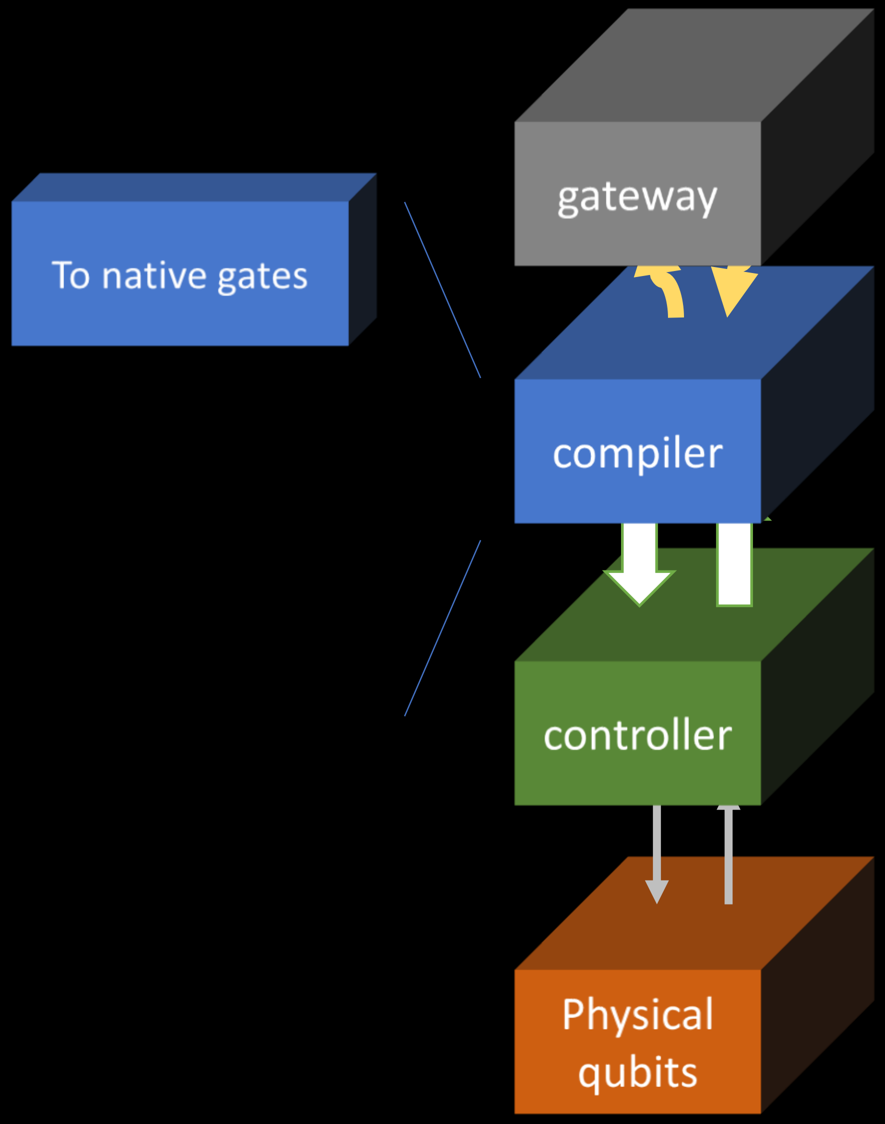


Converting a circuit to a pulse sequence

Conversion to native gates

- connectivity





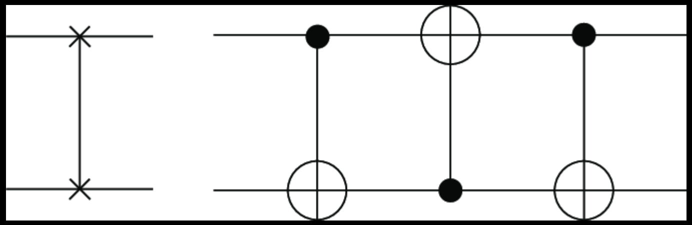
Converting a circuit to a pulse sequence

Conversion to native gates

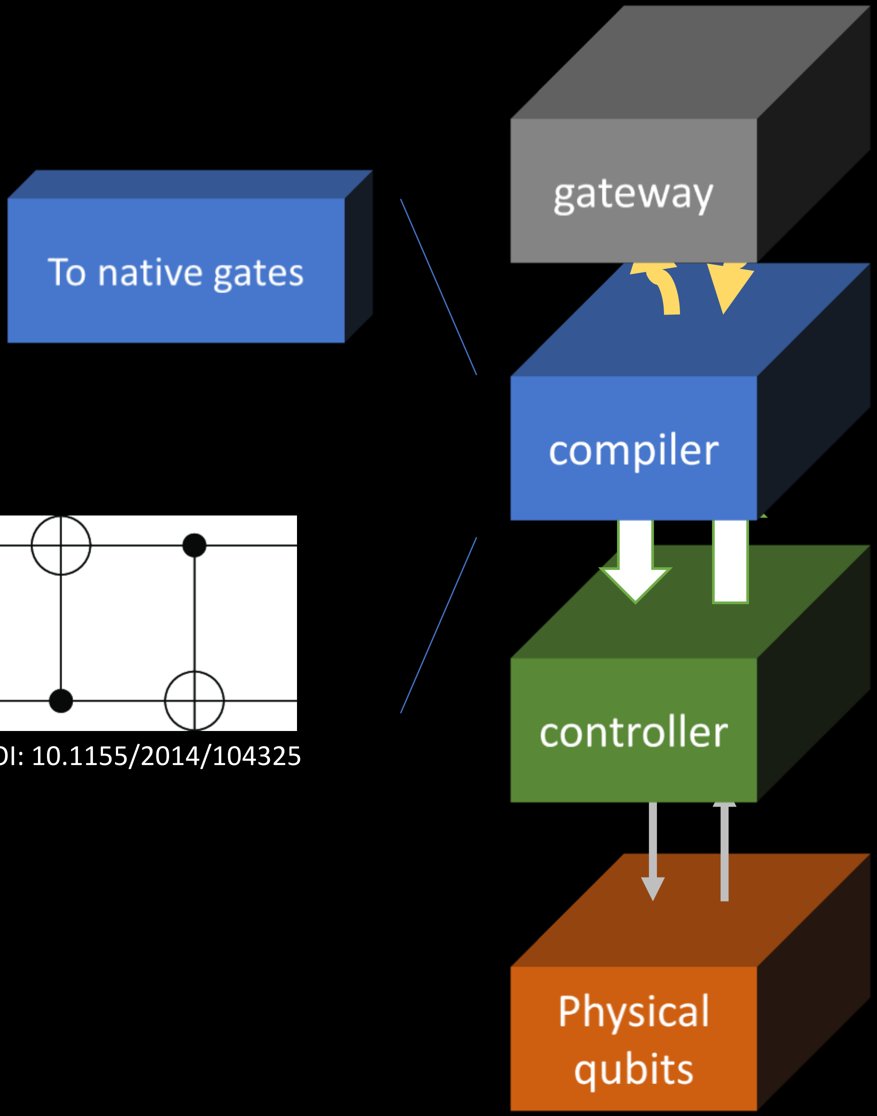
- Universal gate set:

  An arbitrary quantum gate can be decomposed into a set of gates that can be executed on the specific computer

- Similar to classical computing (NAND)



Source: Khalaf et al., DOI: 10.1155/2014/104325



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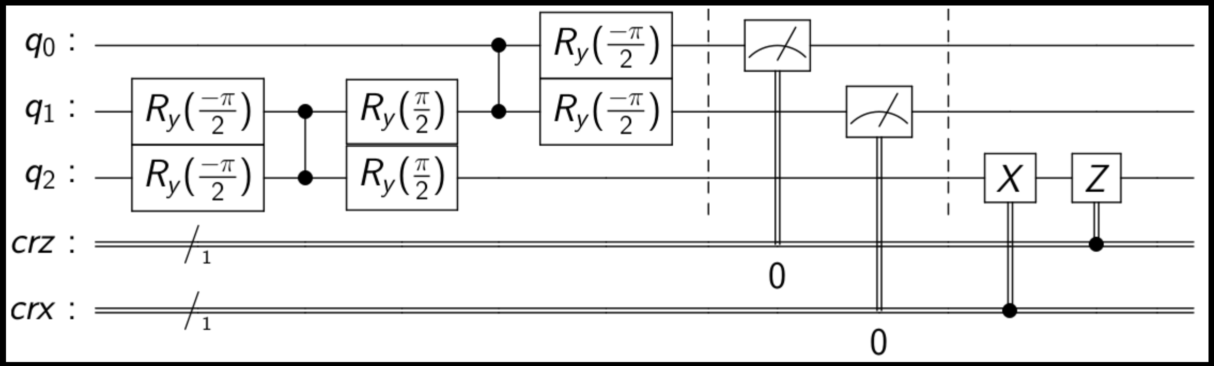
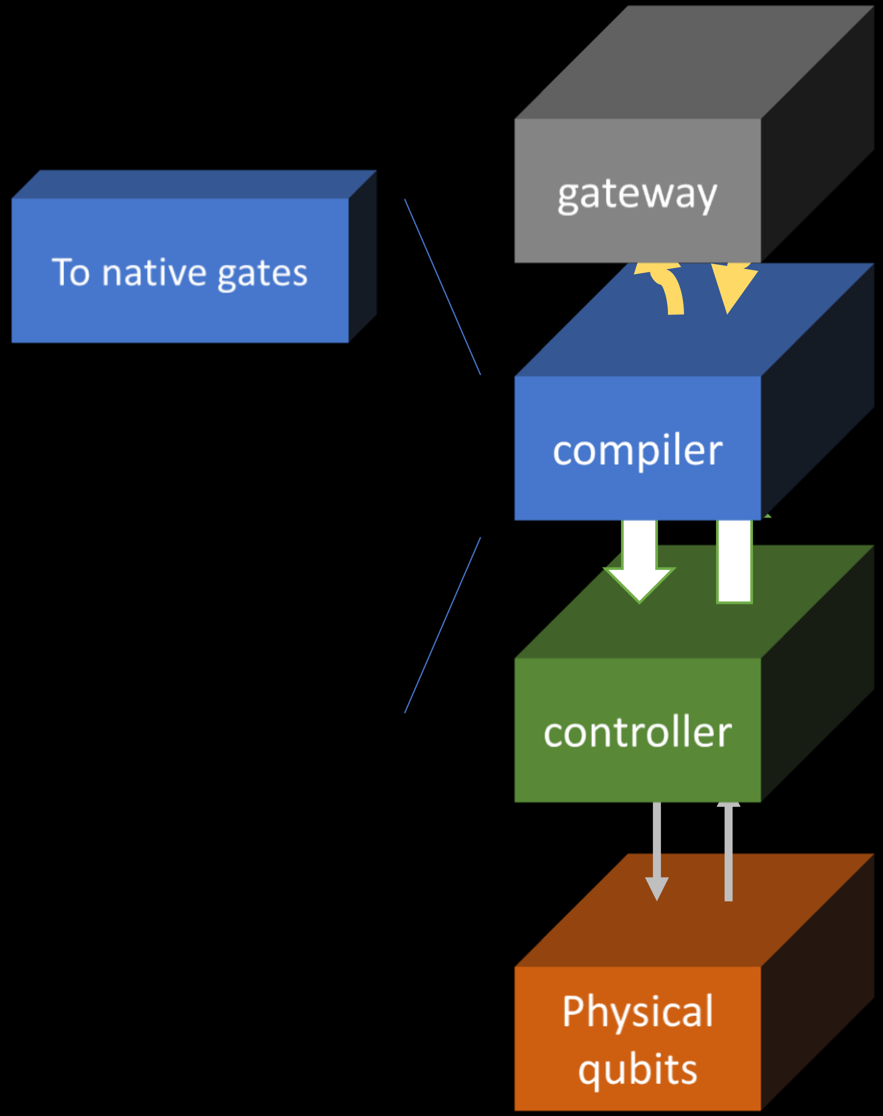
Converting a circuit to a pulse sequence

Conversion to native gates

- Native gates can be
  - effectively implemented on the control hardware
  - are *directly* translated to pulses





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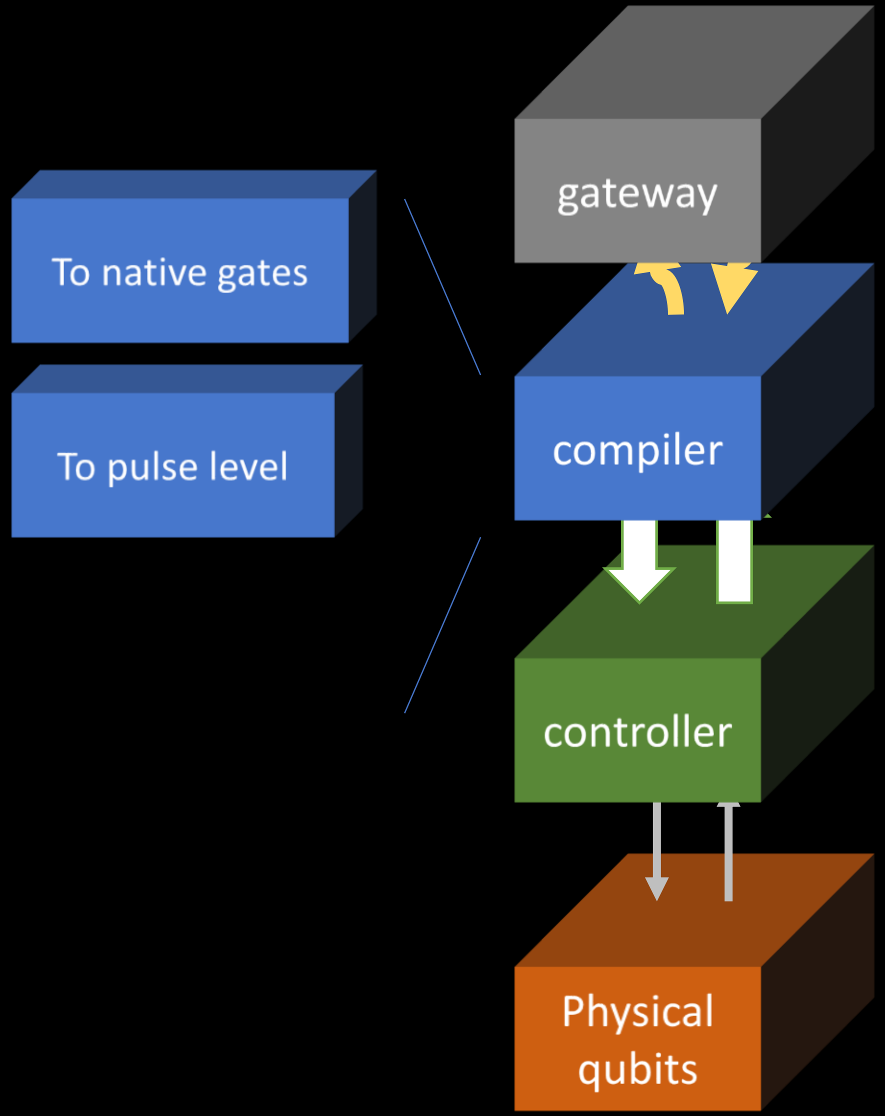
Converting a circuit to a pulse sequence

Conversion to pulse level

- Pulse scheduling
  - Precise timing of pulses that implement desired circuit



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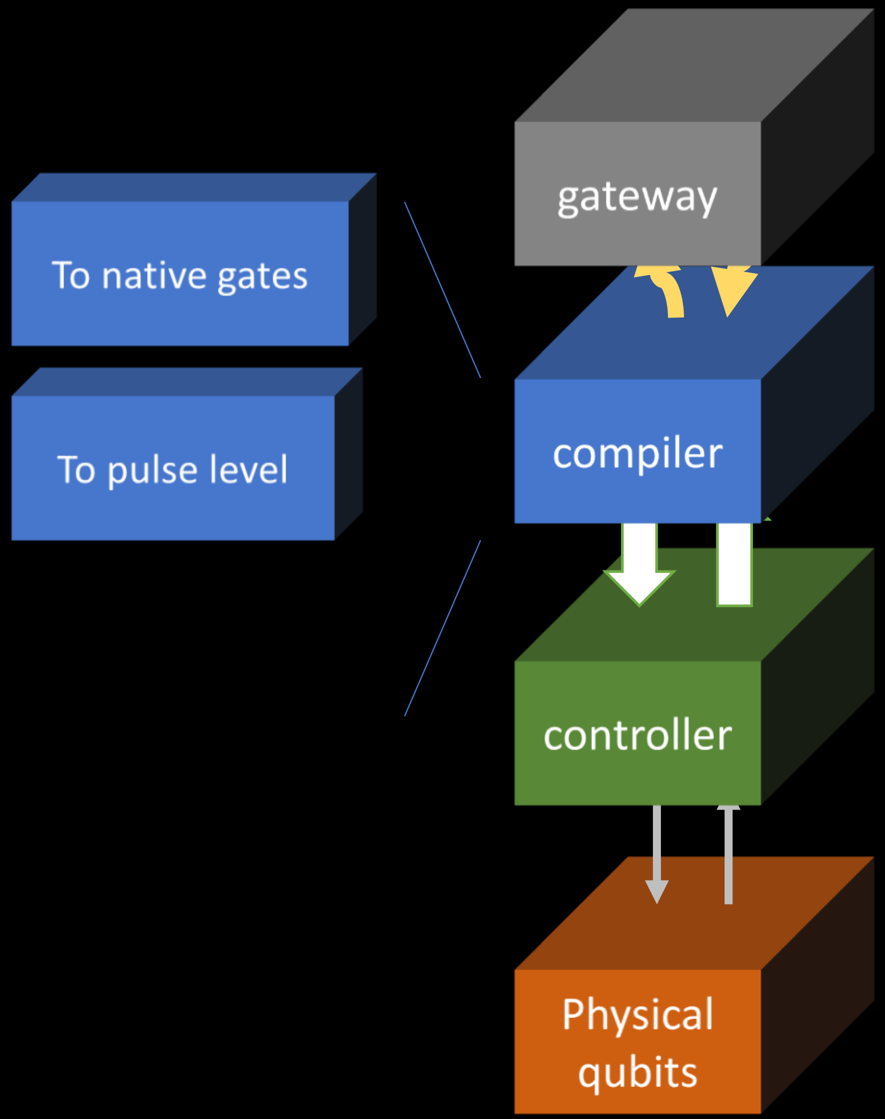
Converting a circuit to a pulse sequence

Conversion to pulse level

- Where should pulses be placed in time?
- Some considerations:
  - Available resources for simultaneous addressing
  - Minimize time in “fragile” states
  - Cross talk
- The goal is to maximize fidelity



Converting a circuit to a pulse sequence

QUA and compilation

```
with program() as prog:
    I = declare(fixed)
    Q = declare(fixed)
    n = declare(int)

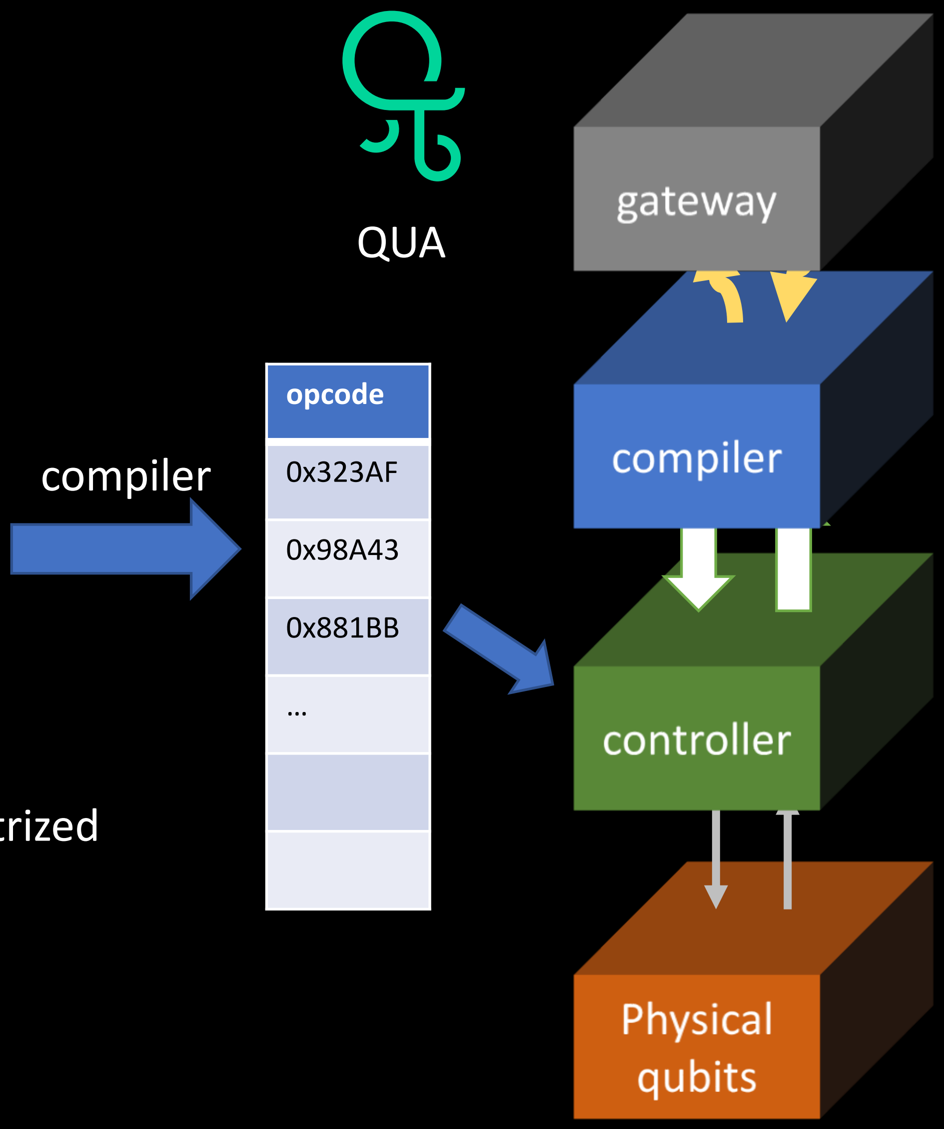
    with for_(n, 0, n < 1000, n + 1):
        reset_q1()
        reset_q2()
        align(*all_elements)
        frame_rotation_2pi('q1', -0.25)
        play('pi_pulse' * amp(0.5), 'q1')
        frame_rotation_2pi('q1', 0.25)
        frame_rotation_2pi('q2', -0.25)
        play('pi_pulse' * amp(0.5), 'q2')
        frame_rotation_2pi('q2', 0.25)
        align(*all_elements)
        play('cz_pulse', 'cpl01')
        frame_rotation_2pi('q1', -0.25)
        play('pi_pulse' * amp(0.5), 'q1')
        frame_rotation_2pi('q1', 0.25)
        frame_rotation_2pi('q2', -0.25)
        play('pi_pulse' * amp(0.5), 'q2')
```

Flow control

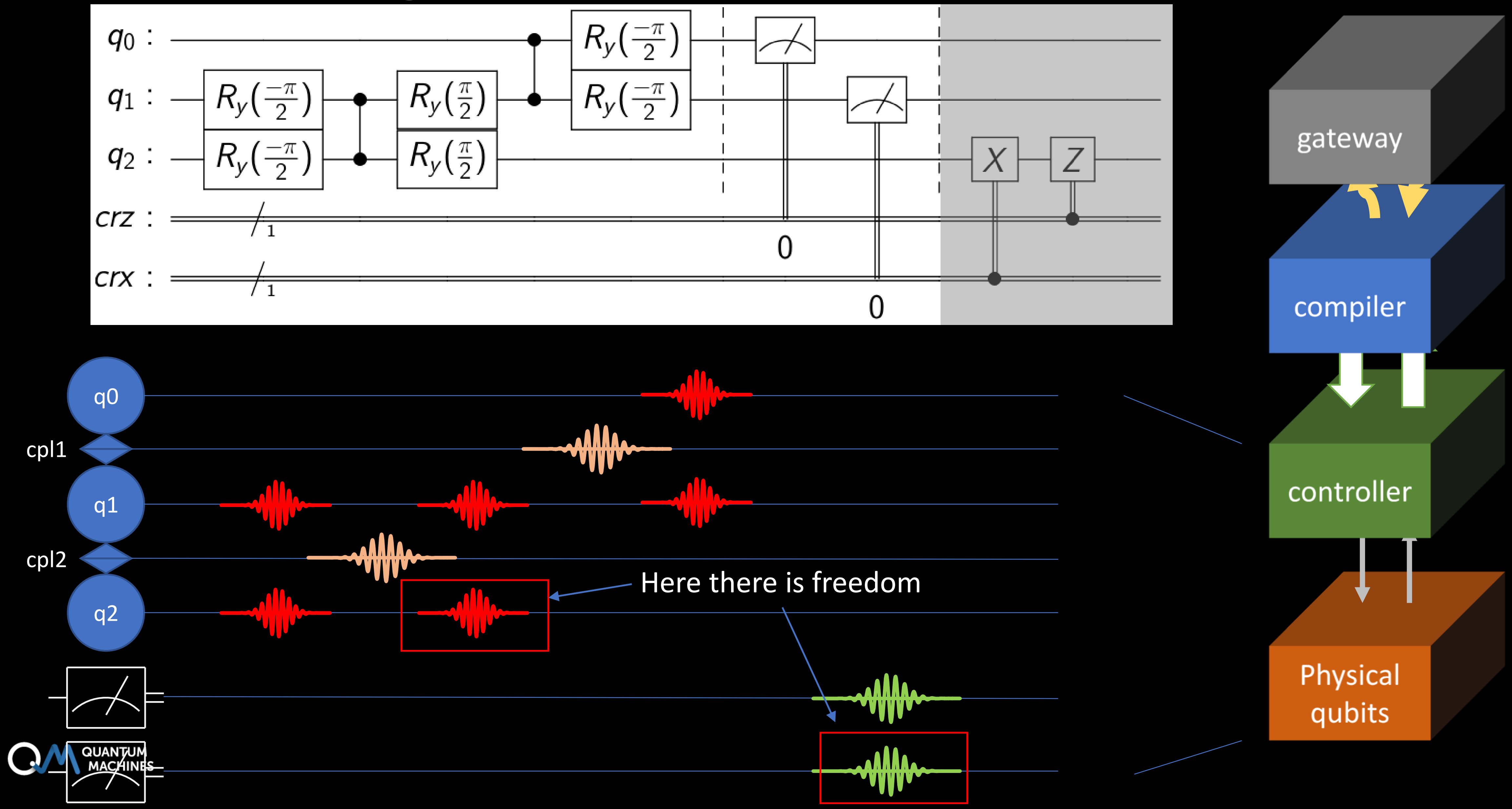
arithmetic

timing

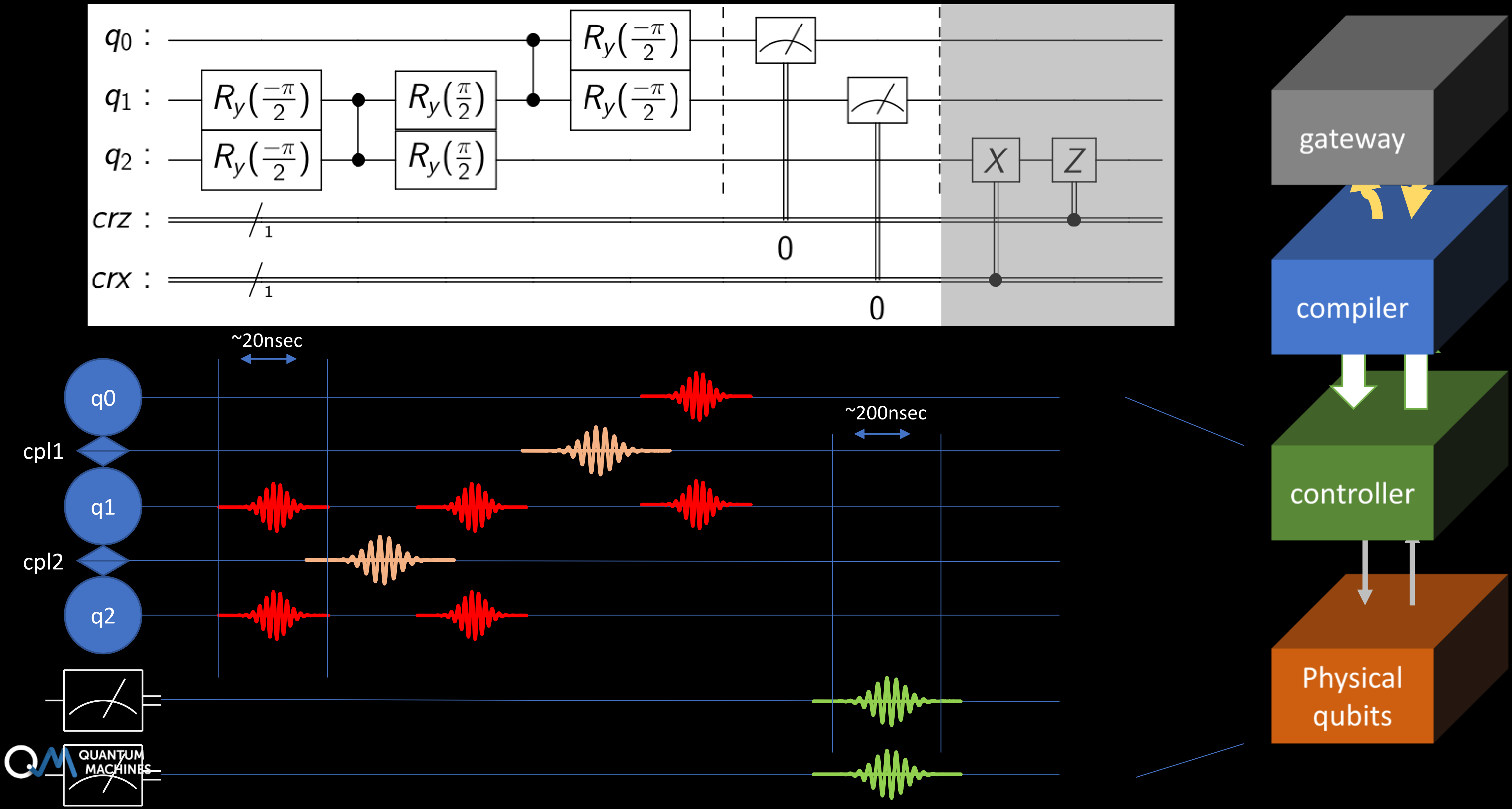
Parametrized pulses



Converting a circuit to a pulse sequence



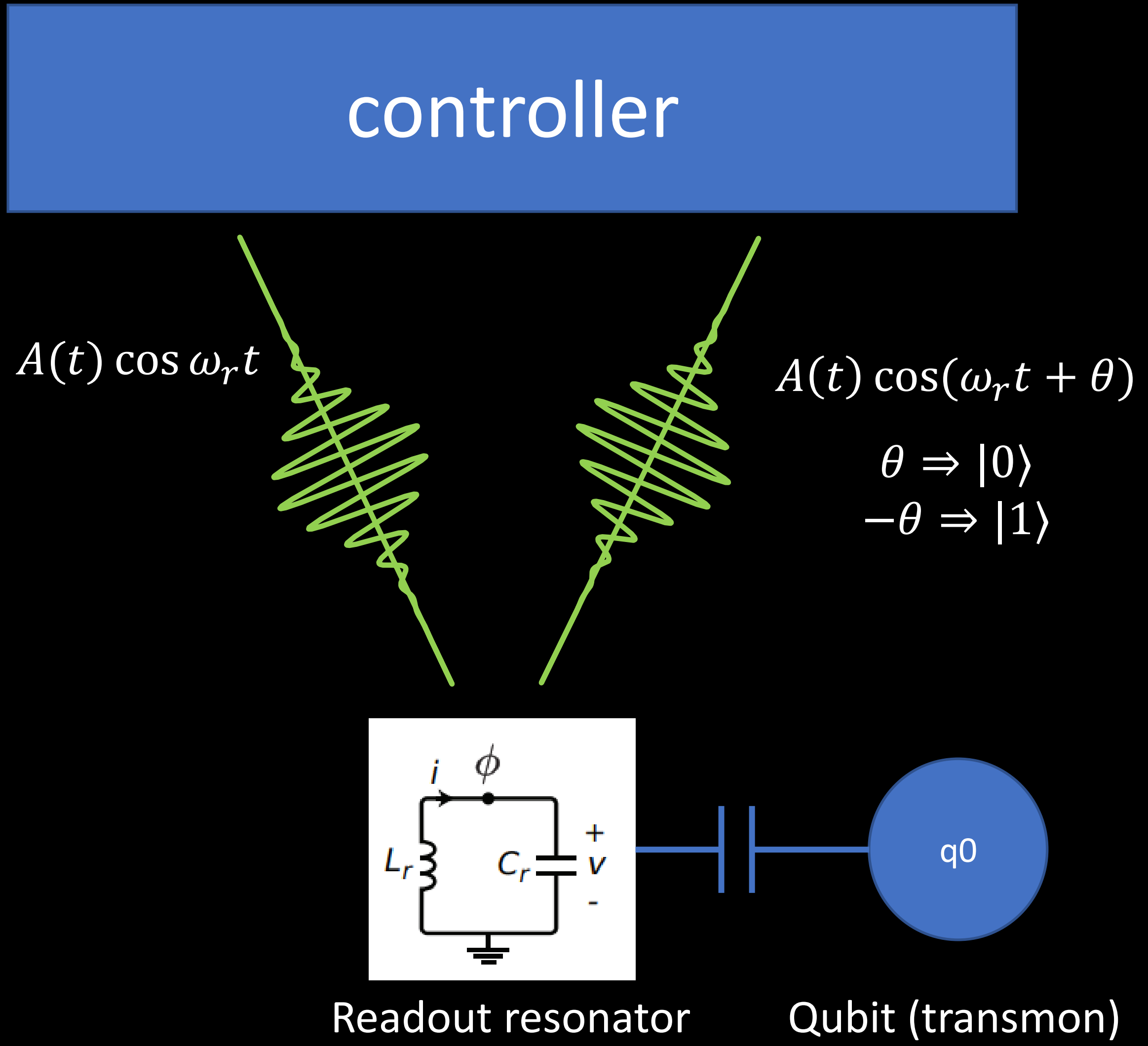
Converting a circuit to a pulse sequence



Converting a circuit to a pulse sequence

Measurement

- How is the state of the qubit measured?
- We send a pulse to an LC resonator
- The resonance frequency shifts due to the state of the qubit
- The phase of the returned pulse determines the state: $|0\rangle$ or $|1\rangle$



Converting a circuit to a pulse sequence

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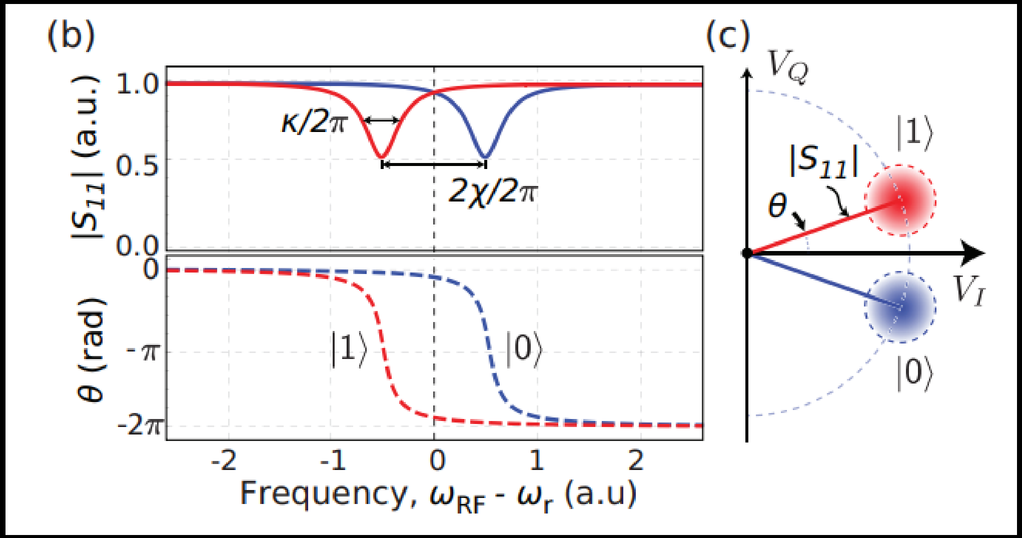
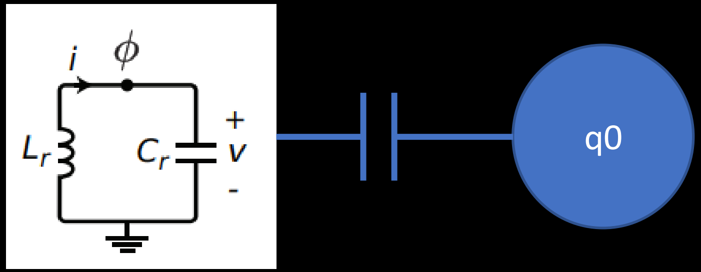


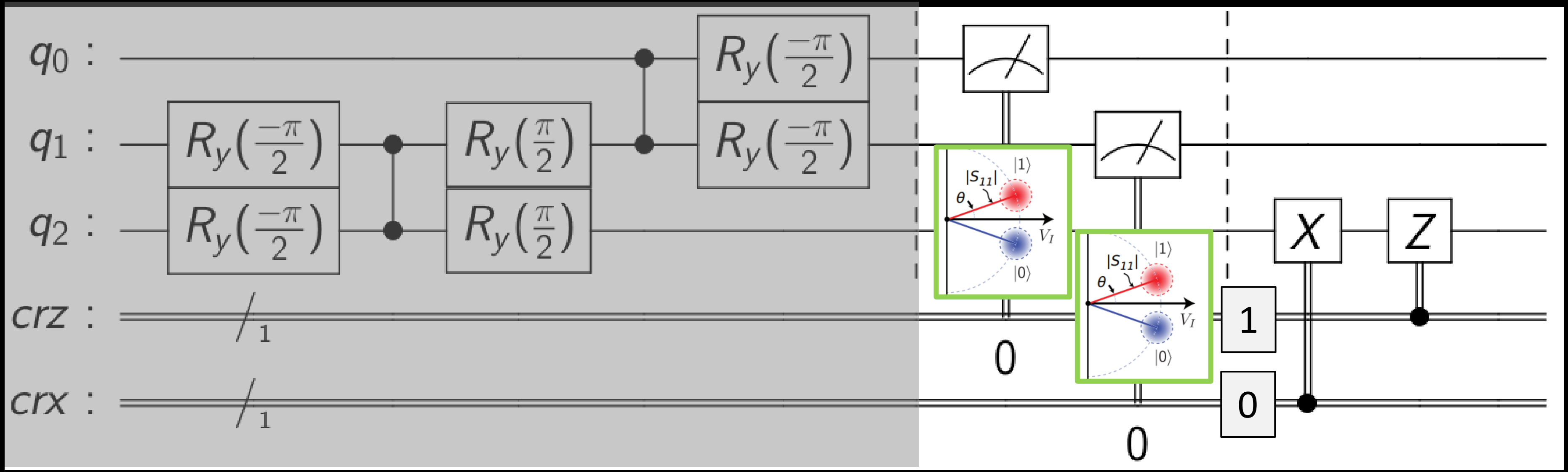
Krantz et al., Applied Physics Reviews 6, 021318 (2019)

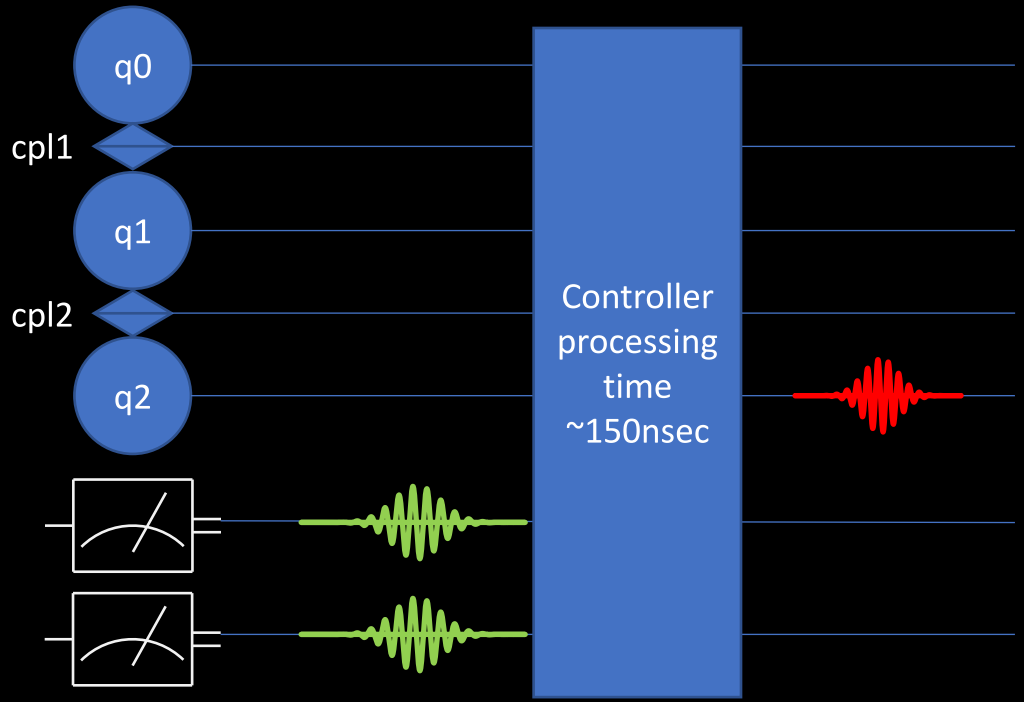


Readout resonator

Qubit (transmon)

The feedback process





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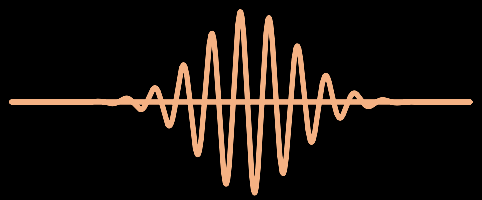
Translating gates to pulses

- Why do RF pulses carry out gates?

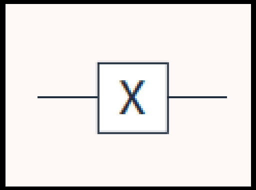
- e.g. why does $R_y(\frac{-\pi}{2})$ =  ?

Single qubit and two qubit gates

- We separate the discussion into two parts
  - Single qubit gates: Universally the same on all platforms
  - Two qubit gates: Many different implementations. We give the general picture and a simple example

Single qubit gates

- Single qubit gates describe rotations of a vector on the Bloch sphere.
- E.g an X rotation
- Every single qubit operation can be mapped to a rotation of the qubit state



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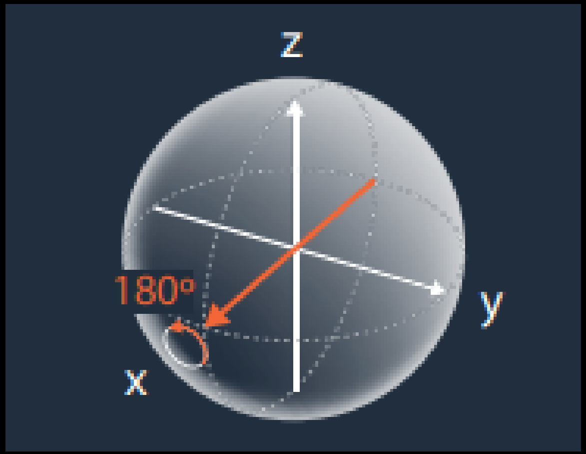

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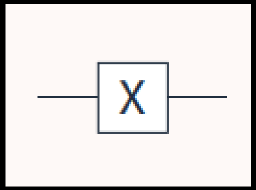
Single qubit gates

- How is this abstract description related to the real physical system?



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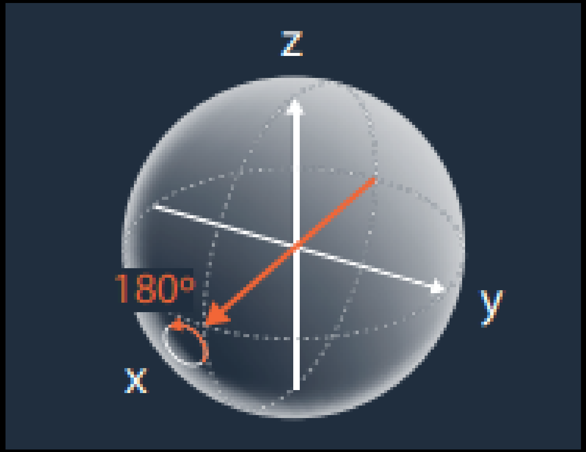
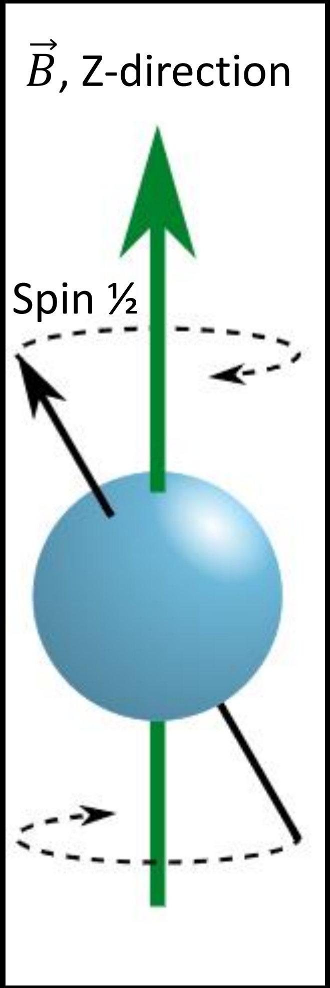
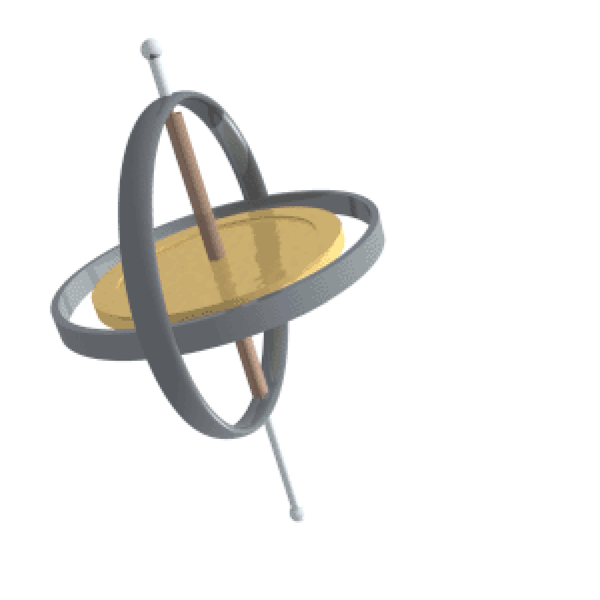


QUANTUM MACHINES

Single qubit gates: XY rotations

- All qubits can be mapped to a **spin ½** in a fixed magnetic field $\vec{B} = \hat{z}B_0$.
- Experimental fact: The tip of this spin rotates on a plane perpendicular to the field.
- This rotation has a fixed frequency $\omega_{01} = \gamma B_0$.

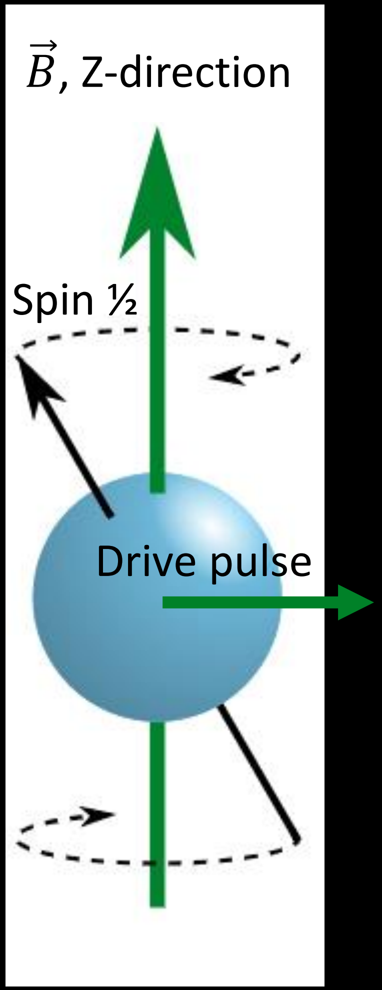


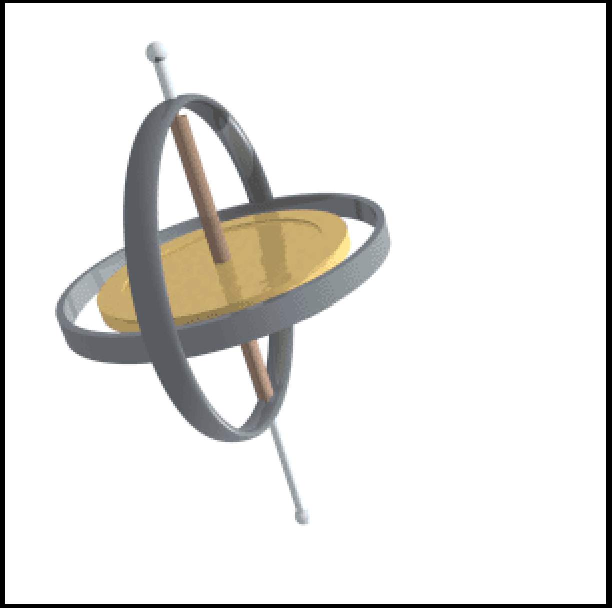


Source: Wikipedia

Single qubit gates: XY rotations

- All qubits can be mapped to a **spin ½** in a fixed magnetic field $\vec{B} = \hat{z}B_0$.
- To flip this spin, we need to send a drive pulse that is resonant with ω_{01}.
- The amplitude of the pulse is proportional to the flip rate.





Source: Wikipedia

QUANTUM MACHINES

Two-qubit gates

- Here the situation is less straightforward
- Nature does not give us a recipe for two qubit gates
- physicists have to come up with clever ways to get the physics to behave as a two qubit gate.
- The main idea is to generate an interaction where the state of one qubit affects the energy of the other:

$$E_{01} + E_{10} \neq E_{11}$$

two qubit gates: a non-exhaustive list

Each gate here requires a different set of pulses!

Trapped ions

- Mølmer–Sørensen gate
- Cirac-Zoller gate
- Geometric phase gate

Cold neutral atoms

- Rydberg blockage gate

cQED (SC qubits)

- Cross-resonance gate (IBM)
- fSim gateset (google)
- Parametrically coupled gates (Rigetti)
- Tunable flux CPHASE

Spin qubits

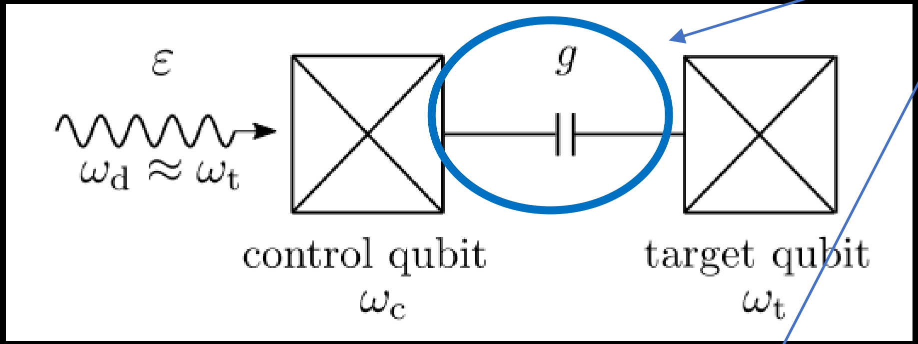
- Exchange coupling gate (DiVincenzo-Loss)
- Exchange coupling gate (Kane)

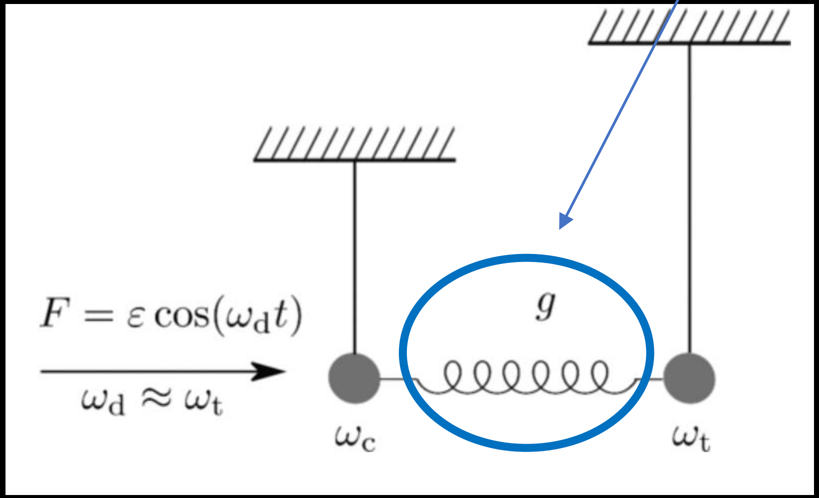
Examples of pulse sequences for some of the gates

CR gate (IBM)

Target qubit is driven through control qubit.

The target will see a different strength signal if control is in $|g\rangle$ or $|e\rangle$ state.





Tripathi et al., PhysRevA.100.012301 (2019)

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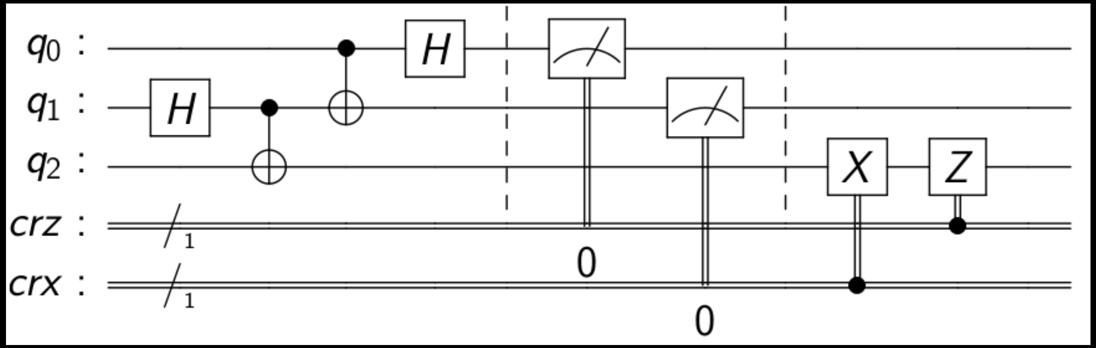
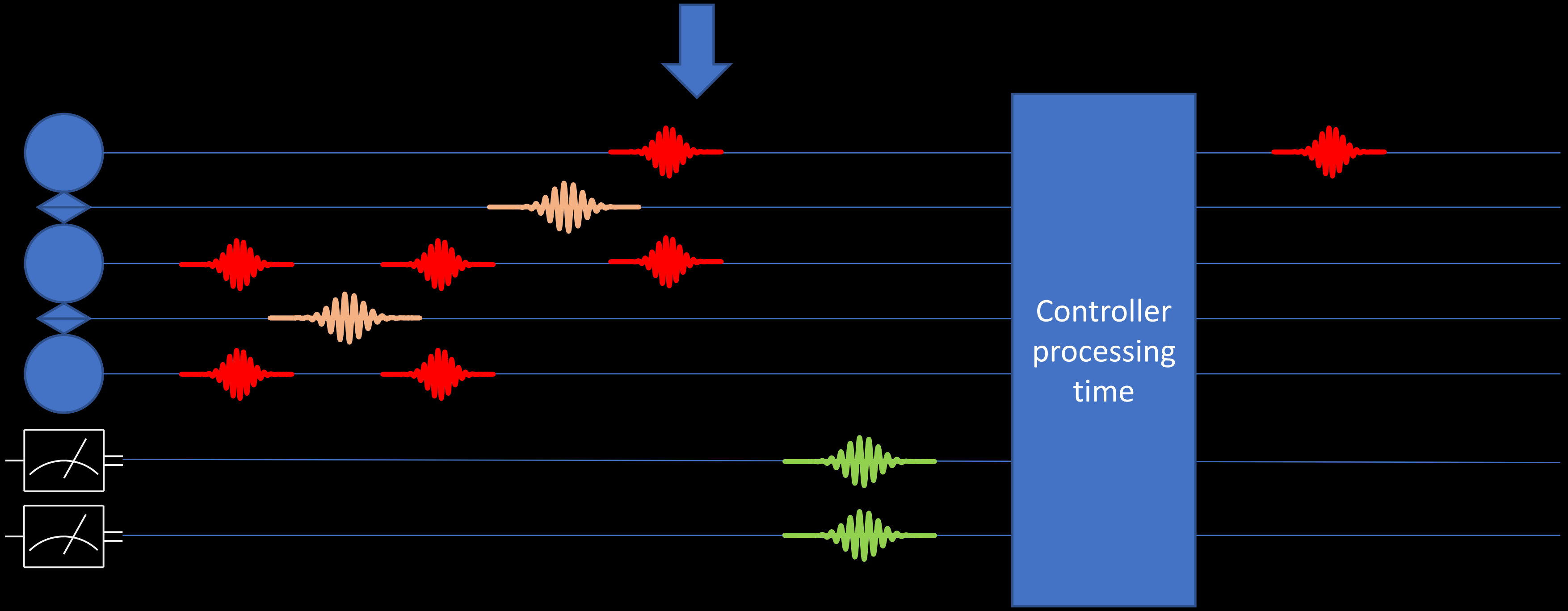
Overall





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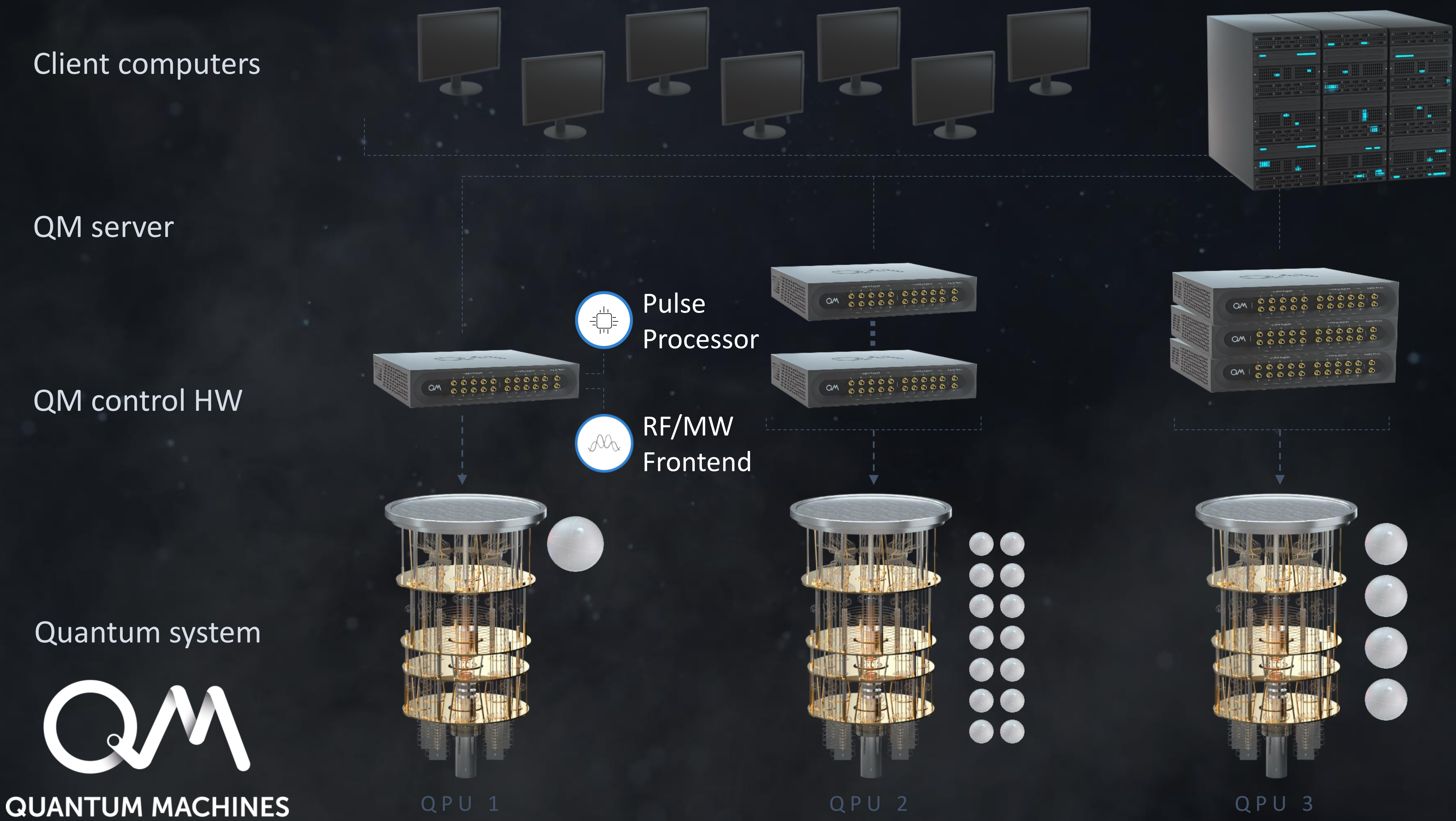
How we are & Job opportunities


Client computers
QM server
QM control HW
Quantum system
Pulse
Processor
RF/MW
Frontend
QPU 1
QPU 2
QPU 3
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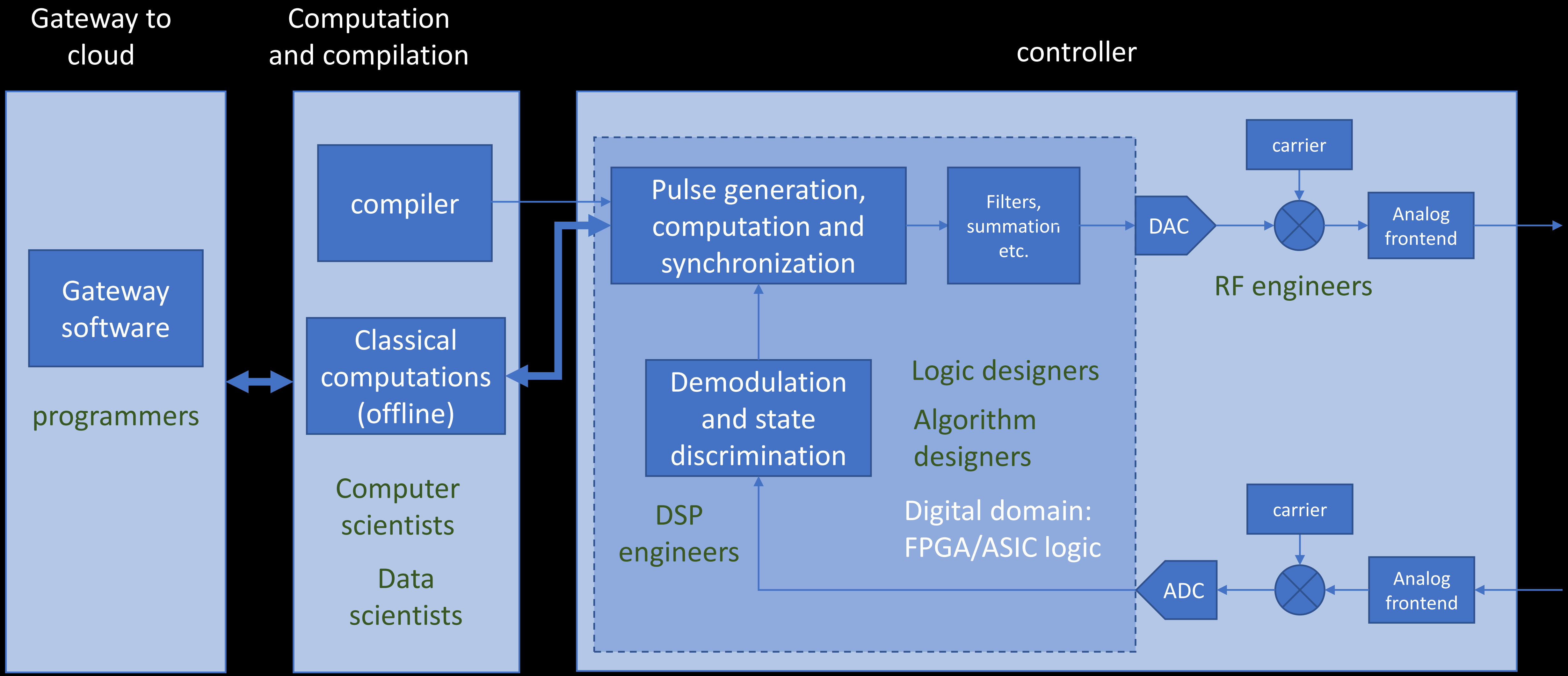
Job opportunities for engineers and scientists



QUANTUM MACHINES

Summary

- The hardware controller sits at the heart of the quantum computing stack.
- It translates from the algorithm supplied by the user into the drive pulses that will actually create the logical circuit.

- The abstract quantum gates get translated into physical drive pulses as we’ve seen.

- There are many opportunities for scientists, programmers and engineers in this emerging field!

Thank you!

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Questions?